YALE
PEABODY
MUSEUM

P.O. BOX 208118 | NEW HAVEN CT 06520-8118 USA | PEABODY.YALE. EDU

JOURNAL OF MARINE RESEARCH

The *Journal of Marine Research,* one of the oldest journals in American marine science, published important peer-reviewed original research on a broad array of topics in physical, biological, and chemical oceanography vital to the academic oceanographic community in the long and rich tradition of the Sears Foundation for Marine Research at Yale University.

An archive of all issues from 1937 to 2021 (Volume 1–79) are available through EliScholar, a digital platform for scholarly publishing provided by Yale University Library at https://elischolar.library.yale.edu/.

Requests for permission to clear rights for use of this content should be directed to the authors, their estates, or other representatives. The *Journal of Marine Research* has no contact information beyond the affiliations listed in the published articles. We ask that you provide attribution to the *Journal of Marine Research*.

Yale University provides access to these materials for educational and research purposes only. Copyright or other proprietary rights to content contained in this document may be held by individuals or entities other than, or in addition to, Yale University. You are solely responsible for determining the ownership of the copyright, and for obtaining permission for your intended use. Yale University makes no warranty that your distribution, reproduction, or other use of these materials will not infringe the rights of third parties.

This work is licensed under a Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License.
https://creativecommons.org/licenses/by-nc-sa/4.0/

Deep Caribbean inflow through the Anegada – Jungfern Passage

by Marvel C. Stalcup[1], William G. Metcalf[1],
and Richard G. Johnson[2]

ABSTRACT

The Jungfern Passage Sill at a depth of 1815 meters is the controlling sill for the deepest water exchange between the Atlantic Ocean and the Venezuelan Basin of the Caribbean Sea. Data from moored current meters and temperature recorders, STD's and hydrographic stations obtained during March and April 1972 are interpreted as indicating an average net flow of 56×10^3 m^3 sec^{-1} of deep Atlantic water into the Caribbean Sea. Current speeds as high as 32 cm sec^{-1} were recorded on the sill near the axis of the inflow, and the average velocity during 38 days was 20 cm sec^{-1}. The temperature and current records show prominent semi-diurnal tidal components. A diurnal component and what may be some shorter seiche periods are also present. A current reversal occurred near the middle of the observational period during which Caribbean water flowed towards the Atlantic at speeds up to 10 cm sec^{-1} for 3 days. The inflow-outflow cycle is described in terms of an expanding and contracting tongue of cold water lying close to sill depth. The low silicate content of the Atlantic water is an especially useful indicator in tracing the extent of this tongue.

As part of a study of the circulation through the passages of the Lesser Antilles (Stalcup and Metcalf, 1972 & 1973) an investigation was made during March and April 1972 of the deep flow of Atlantic water through the Anegada – Jungfern Passage into the Venezuelan Basin of the Caribbean Sea (Figure 1). This study employed moored current meters and temperature recorders to monitor the near bottom flow over the Jungfern Sill and a salinity–temperature–depth (STD) sensor to measure the thickness and delineate the areal extent of the inflowing water. Water samples were collected in a modified "rosette sampler" and analysed both to calibrate the STD and to determine the dissolved oxygen and silicate content.

1. Bathymetry

Earlier bathymetric surveys (Frassetto and Northrup, 1957; Sturges, 1970; and Ross and Mann, 1971) in this area show that the Anegada – Jungfern Passage

---

[1] Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543.

[2] University of Michigan M & O Department, Ann Arbor, Michigan 48104. Present Address: Industrial Biotest Lab., Northbrook, Illinois 60062.

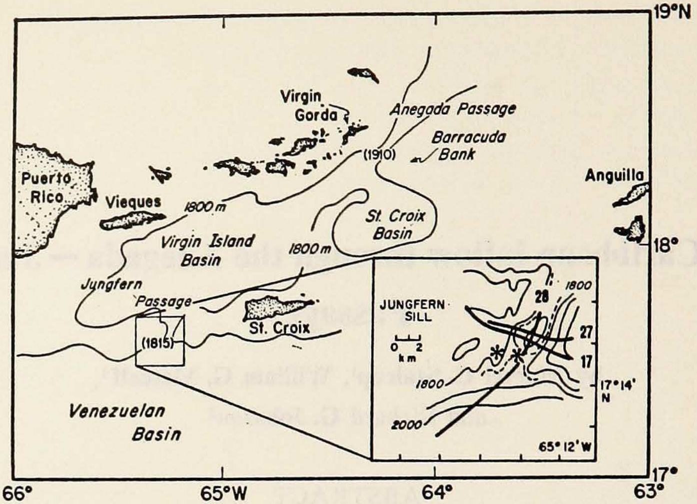

Figure 1. Anegada – Jungfern Passage region. The depths of the two main sills are shown in parentheses. The inset shows the locations of the current meters (*) and the tracks of STD stations 17, 27, and 28 in the Jungfern Sill area.

contains two main sills separated by the deep (4500 m) Virgin Islands Basin. The Anegada Sill is located at the northeastern end of this basin and separates it from the Atlantic Ocean. The Jungfern Sill is at the southwestern end of the basin and separates it from the Venezuelan Basin of the Caribbean Sea.

Since the deep flow must be at least partly controlled by the topography in this passage the present study began with a detailed bathymetric survey of the Anegada and Jungfern Sills (Stalcup and Metcalf, 1973).

The possibility was considered that a deeper connection between the Virgin Island Basin and Venezuelan Basin in the Caribbean Sea might exist in the less well charted region east of the island of St. Croix. A brief bathymetric survey was carried out, and it was determined that the sill in that area could be no deeper than 1644 m and might be shallower. This is roughly 200 m shallower than the controlling depth of the Jungfern Sill southwest of St. Croix.

A highly detailed bathymetric survey southwest of St. Croix charted the topography on and near the Jungfern Sill and found it to be essentially identical to that described by Sturges (1970). The sill is located at the lowest point in the ridge joining Puerto Rico and St. Croix Island. The complexity of the topography in this region is illustrated by the presence of two sills separated by a depression 6 km long with depths to 1970 m. The northern sill is about 1830 m deep and the southern one at 17°35′N, 65°14′W, is 1815 m.

The Anegada sill, at 18°22′N, 64°16′W, was found to be in a steep valley in the ridge joining Virgin Gorda Island and Barracuda Bank. The maximum depth of this sill is 1910 or 300 m shallower than the sill at 18°13′N, 64°32′W described by Frassetto and Northrup (1957). U.S. Naval Oceanographic Office bathymetric charts (Nos. 25008 and B0704) indicate that the Anegada Sill surveyed during this study is the controlling sill for the Virgin Islands Basin.

The ridge east of Barracuda Bank separates the St. Croix Basin ($\simeq$ 3000 m) from the Atlantic Ocean. The characteristics of the deep water show that this basin does not contribute an identifiable portion of the flow over the Jungfern Sill. Therefore the bathymetry of this ridge was not included in the survey.

2. Previous work

Worthington (1966) observes that in the Anegada – Jungfern Passage at depths considerably shallower than the controlling depth of the Jungfern Sill, Atlantic water is present that is colder, more saline and consequently denser than the deep Caribbean water. He points out, however, that he saw no evidence to show that this water is presently cascading into the Venezuelan Basin and speculates that a permanent current flowing toward the west along the Jungfern Sill, would balance the observed horizontal density gradients. This current would thus produce a "dynamic" sill shallower than the true geographic sill. Ross and Mann (1971) calculate that the observed density gradients would require a vertical shear of 16 cm sec^{-1} between 1700 m and the sill depth (which they believed to be 1870 m) to prevent deep water from entering the Caribbean.

As part of an investigation of the deep inflow into the Venezuelan Basin, Sturges (1970, 1975) used a salinity-temperature-depth sensor (STD) to delineate cold Atlantic water found near the bottom at the Jungfern Sill. These studies demonstrated that the STD's capability of making continuous measurements of temperature, salinity and depth during a series of closely spaced soundings make it uniquely suited for a survey of this type. Observations at the Jungfern Sill were made while raising and lowering the STD through the bottom 150 m of the water column as the ship drifted slowly downwind across the sill. Careful measurements of the salinity and temperature structure showed that Atlantic water, with temperatures less than 4°C, was present near the sill as an easily recognizable bottom layer 70 m thick. This layer became much thinner after crossing the sill and was traced for several kilometers inside the Venezuelan Basin.

3. Present study

A Hytech model # 9040 STD was used during the present study to delineate the thickness, areal extent and structure of the $< 4°\mathrm{C}$ Atlantic water near both the Jungfern and Anegada Sills. This instrument measures salinity to $\pm 0.03^0/_{00}$, temperature to $\pm 0.02°\mathrm{C}$ and depth to $0.5^0/_0$. A General Oceanics rosette sampler, modified to trip Nansen bottles, was attached to the STD and used to obtain water samples. These samples were analysed aboard ship for salinity, dissolved oxygen and reactive silicate. Salinity was measured using a Woods Hole Oceanographic

Institution conductivity bridge (Schleicher and Bradshaw, 1956) which has an accuracy of ± 0.003 ‰. Dissolved oxygen was determined with a modified Winkler method using an amperometric end point indicator and is believed accurate to 2 %. Reactive silicate was determined using the spectrophotometric method of Grasshoff (1964) which is considered accurate to better than ± 0.5 μg-atoms/l. Standard deep-sea reversing thermometers measured temperatures to ± 0.01°C and depth to ± 0.5 %. Both the thermometric observations and the shipboard salinity determinations were used to calibrate the STD. The two sets of temperature data agreed to within ± 0.02°C and therefore no corrections were applied to the STD data. The STD depth measurements and the thermometrically determined depths differed by – 8 ± 8 m and a correction of – 8 m has been applied to these data. The salinities have been corrected by – 0.05 ‰ for STD stations # 1 to # 14 and by – 0.08 ‰ for the remainder of the stations made during this study. Previous experience with STDs indicates that errors of this magnitude are not uncommon.

Most of these stations were begun upwind (east-northeast) from the Jungfern Sill and off to one side of the patch of cold near-bottom water. As the ship drifted slowly downwind the STD was lowered to within 4 or 5 m of the bottom using a bottom finding pinger (Ocean Research Equipment model # 260) for depth control. Careful measurements were made of the salinity and temperature of the water and the depth of the STD. It was then raised approximately 200 m and then lowered again during which continuous analog traces of temperature and salinity versus depth were recorded. These series of measurements were repeated until the ship had drifted across the sill and the STD record no longer showed the presence of a cold bottom layer. Water samples were collected at several locations to calibrate the STD and for the determination of dissolved oxygen and silicate. Although most stations were made while drifting downwind across the sill, several were occupied while steaming slowly down the axis of the channel to trace the cold water into the Venezuelan Basin. During these steaming stations the measurement techniques were identical to those outlined above.

An observed temperature of 4°C was always found within the sharp temperature gradient which marks the upper boundary of this layer. At the depth of the sill (1815 m) this represents a potential temperature, t_p, of approximately 3.85°C. For convenience we are using a t_p of 3.8°C as representing the top of the layer of deep Atlantic water with which we are primarily concerned in this study of deep Caribbean inflow. A continuous plot of the layer thickness was kept to show the areal extent and thickness of the inflowing water and to monitor temporal changes in the size, thickness, position and minimum temperature in this layer. The ship's position was determined at 10–15 minute intervals by radar ranges and bearings to anchored buoys (Stalcup and Metcalf, 1972) and showed that the ship usually drifted downwind at 60 ± 10 cm sec^{-1}. The resulting wire angles were as great as 50° and produced large (up to 1.5 km) horizontal displacements between the ship and the STD. The following procedure was derived for estimating the position of each STD observation. A bathymetric profile along the track of the station drift was plotted using data recorded by the ship's echo sounder. The water depth at each STD observation was determined by adding the distance off the bottom (as measured by the bottom finding pinger) to the depth measured by the STD and these soundings were plotted versus distance. Then, assuming that the STD followed the course of the ship's track during the drifting station, the bathymetric profile was fitted to the station depth profile and the geographic position of each STD observation was determined. Of the several plotting techniques tested this procedure produced the most consistent results.

Hindsight suggests that possibly a better technique would have been to measure the slant range to the STD with the bottom finding pinger and combine this information with the depth measured by the STD to determine the horizontal displacement. Then, still assuming that the bearing to the STD is back along the ships track, the position of the STD relative to the ship is easily determined.

4. Results

Dissolved silicate concentrations at temperatures between 4° and 5°C have been used (Richards, 1958) to distinguish between Atlantic and eastern Caribbean water types. Silicate values as high as 35 μg-atoms/l are found below sill depth in the Venezuelan Basin while Atlantic water in the same temperature range typically contains 15–16 μg-atoms/l. (See Metcalf, Stalcup and Zemanovic, 1971 & 1973.) Thus Atlantic water is easily recognized whenever it penetrates into the Venezuelan Basin.

The potential temperature measurements obtained during three typical STD stations are shown in Figure 2. The top profile (Figure 2A) is constructed with data from Station # 17 which was occupied on April 12, 1972 while the ship was drifting westward across the central depression in the Jungfern Sill area north of the controlling sill itself. This profile shows that the bottom layer, with potential temperatures less than 3.80°C and with dissolved silicate concentrations of 17–18 μg-atoms/l, was less than 100 m thick, and that the upper surface of this layer was deeper than the Jungfern Sill (1815 m). These data suggest that none of the cold, silica-poor Atlantic water found in the bottom of this depression was flowing into the Caribbean on April 12. Measurements from current meters anchored at two sites on the sill (to be described later) show a current flowing northeast out of the Caribbean with velocities close to sill level of up to 8 cm sec^{-1} from April 10–13. *In situ* temperatures recorded by one current meter 8 m above the bottom near the center of the sill averaged 4.20°C (t_p = 4.04°C) during this period. The other seven STD stations made near the sill during the April 12–13 period measured temperature structures similar to that shown here and indicate that this profile is probably typical of periods when the flow over the Jungfern Sill is directed northeast, out of the Caribbean.

The potential temperature profile shown in the Figure 2B was constructed from data obtained on April 19 during STD station # 27, located slightly north of STD

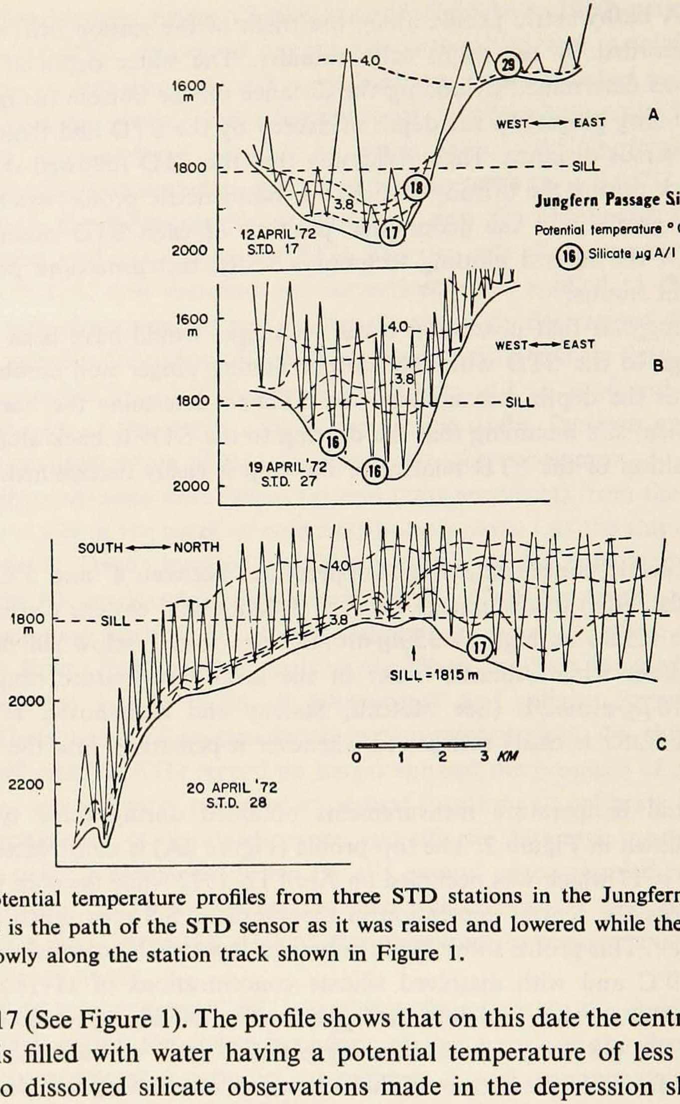

Figure 2. Potential temperature profiles from three STD stations in the Jungfern Sill area. The zig-zag line is the path of the STD sensor as it was raised and lowered while the ship drifted or steamed slowly along the station track shown in Figure 1.

Station # 17 (See Figure 1). The profile shows that on this date the central depression in the sill is filled with water having a potential temperature of less than 3.80°C, and the two dissolved silicate observations made in the depression showed values of 16 μg-atoms/1, typical of Atlantic water at the observed temperature. The cold water layer is now three times as thick in this area as on April 12, and the depth of the 3.80°C t_p isothermal surface is almost 100 m shallower than the Jungfern Sill. These temperature data indicate that on April 19 cold Atlantic water could be cascading over the Jungfern sill into the Venezuelan Basin, and on this date the anchored current meters measured a current flowing southwest into the Caribbean with velocities up to 27 cm sec^{-1} measured 8 m above the bottom. Potential temperatures as low as 3.67°C were found at the bottom. Thus, between April 12 and 19 the potential temperature of the water flowing over the sill decreased from 3.95°C, when the flow was out of the Caribbean, to 3.67°C, when the flow was directed into

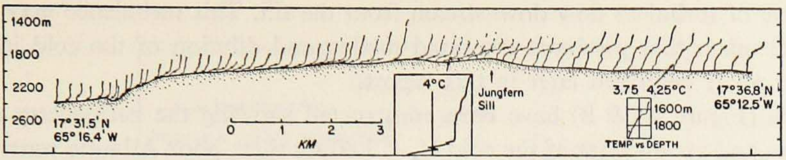

Figure 3. Temperature-depth traces from STD station # 28, April 20, 1972 (see Figure 1 for location). The dots represent the 4°C *in situ* temperature ($t_p \simeq 3.8$°C). The bottom of each trace marks the geographical position. Inset at right shows temperature scale. Inset at left shows an inversion believed to indicate turbulence near the sill (see text).

the Caribbean. All of the STD and current meter data show this correlation. When the upper surface of the cold layer of Atlantic water lies deeper than the Jungfern Sill the flow at sill level is either weak or directed out of the Caribbean, and potential temperatures on the sill are greater than 3.80°C. When the upper surface of the layer lies shallower than the sill the flow is into the Caribbean with observed velocities as high as 32 cm $\sec^{-1}$, and potential temperatures on the sill are as low as 3.62°C.

The bottom diagram (Figure 2C) is the potential temperature profile from STD Station # 28 made on April 20 while the ship, starting at the northern end of the central depression, steamed slowly southwest along the axis of the channel, over the sill, and into the Venezuelan Basin. The 3.80°C potential temperature isotherm was traced 7.5 km into the Venezuelan Basin to a depth of 2300 m where it disappeared. North of the sill the layer was 130 m shallower than the sill. One kilometer south of the sill the thickness of this southward flowing layer was reduced to 60 m. On this date a current meter situated eight meters above the bottom near the middle of the sill and close to this profile, recorded current velocities averaging 26 cm $\sec^{-1}$ toward the southwest. The average potential temperature on the sill during this period was 3.67°C. The direct current measurements and the STD observations indicate that STD Station # 28 was made along the axis of the flow. Assuming that this is the case and that the current did not meander off to one side, this profile illustrates the large downstream slope of the isotherms over the sill and the intensification of the thermocline as the water flows over the sill. It also demonstrates how quickly the cold Atlantic water mixes with Venezuelan Basin water as it flows down the steep slope into the basin.

Tracings of the temperature-depth records obtained during STD Station # 28 (Figure 3) show the character of the near-bottom thermal structure in the inflowing water. The bottom of each trace defines the geographic position of the STD lowering. The dots on the T/D curves mark the depth of the 4°C *in situ* temperature ($t_p \simeq 3.80$°C) and in a general way define the upper surface of the layer we are concerned with. In the depression the average vertical temperature gradient is 0.002°C/m, while over the sill the gradient increases to 0.01°C/m. One of the STD lowerings just south of the sill shows a marked temperature inversion (see inset in Figure 3) which is probably indicative of turbulent flow downstream from the sill. This turbulence may well be the mechanism that produces the rapid mixing and dilution of the cold inflowing Atlantic water described later in this report.

Charts (Figure 4A & B) have been constructed showing the bathymetry and the thickness and areal extent of the cold ($t_p < 3.80°C$) silica-poor Atlantic water during April 12–13, and April 18–25, 1972. The dots represent the positions of the STD when it was within 4–5 m of the bottom during each lowering. The lines of dots indicate the station tracks, and the circled numbers are the near-bottom silicate values in μg-atoms/l. The absence of cold water over the sill and inside the Venezuelan Basin and the high silicate values south of the sill clearly show that Atlantic water was not flowing over the sill during the earlier period. The cold water is limited to a layer less than 100 m thick confined to the depression in which the depth is greater than 1900 m. This layer has silicate values typical of Atlantic water.

As shown in Figure 4B (also see Figures 2C and 3) the thickness and distribution of the cold bottom layers during the period of strong inflow was quite different from what it had been a week earlier (Figures 2A and 4A). STD stations during this strong inflow period show the central depression in the ridge to be filled with a layer of cold, silicate-poor Atlantic water greater than 250 m thick. The 3.80°C t_p isotherm extends into the Venezuelan Basin as an irregular plume 8 km long and 5 km wide and approximately 40 m thick. This cold near-bottom layer can be traced from the sill (1815 m) downslope into the basin to a depth of 2300 m. At positions near the sill, dissolved silicate values of 16–19 μg-atoms/l were measured where one week earlier values had been 29–30 μg-atoms/l.

The intensification of the thermocline, the steep slope of the 4°C isotherm, and the downstream turbulence observed during the period of strong inflow (Figures 2C, 3 and 4B) present a picture similar to that shown by Whitehead, Leetma and Knox (1974). They address the problem of flow through straits and over sills by considering the sill to be analogous to a weir or dam and point out that the depth of water over a dam controls not only the velocity and transport of the flow but also the depth of water upstream from the dam. This theory is expanded to include two-layered flow in a rotating model and uses the following formula (number 3.15 in Whitehead, *et al*) to calculate the transport (Q'_m) of cold Atlantic water over the Jungfern Sill:

$$Q'_m = (2/3)^{3/2}\, b g'^{1/2} \left[h_u - \frac{f^2 b^2}{8g'}\right]^{3/2}$$

where b = the width of the sill
f = the Coriolis parameter
g' = the reduced gravity
and h_u = the thickness of the layer above sill depth.

Using values from the Jungfern Passage of

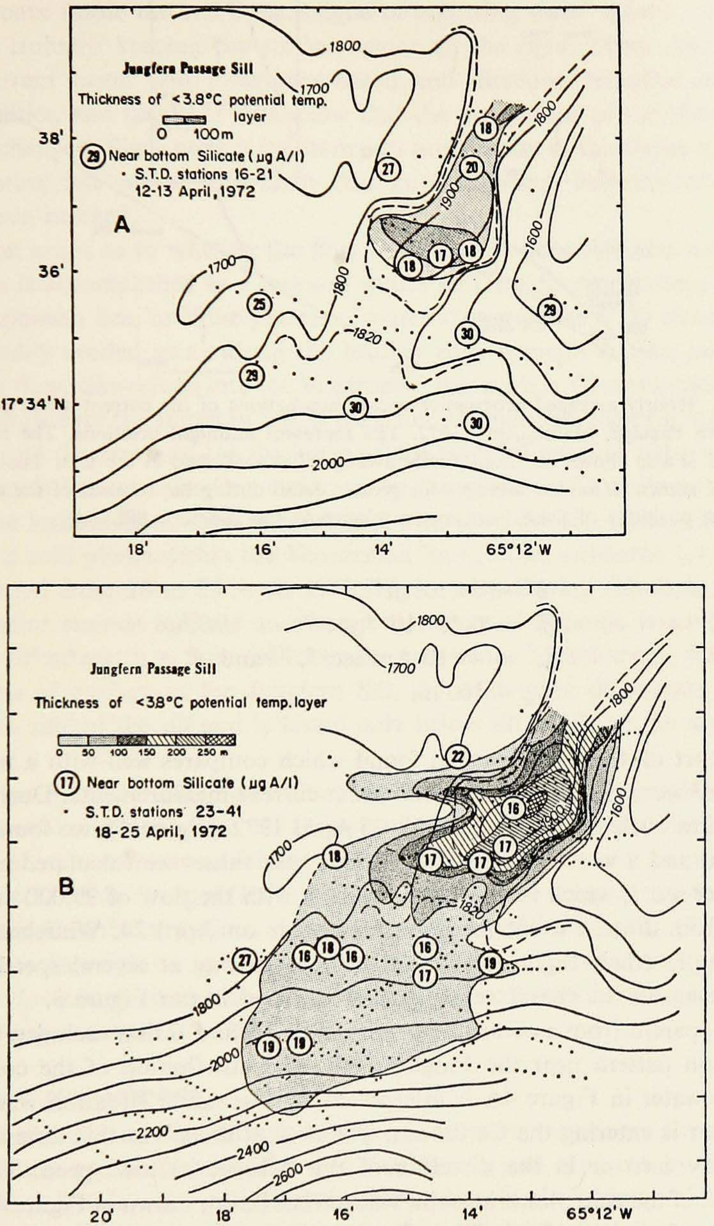

Figure 4. Thickness of the deep cold layer ($t_p = < 3.8°C$) near the Jungfern Sill during 12–13 April (A) and 18–25 April (B). Bathymetry after Stalcup and Metcalf (1973).

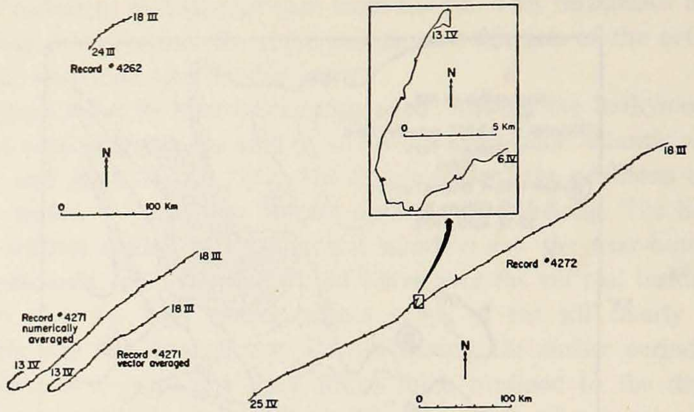

Figure 5. Hourly averaged progressive vector summations of the current meter records from the Jungfern Passage, March–April 1972. Tics represent midnight positions. The record for meter # 4271 is also shown as "numerically averaged" as described in the text. The inset for record # 4272 shows 15 minute averages for greater detail during the reversal of the current. Table 1 lists the positions of these instruments relative to the Jungfern Sill.

$$
\begin{aligned}
b &= 5\times 10^{3}\ \text{m} \\
f &= 0.45\times 10^{-4}\ \text{sec}^{-1} \\
g' &= 4\times 10^{-4}\ \text{m sec}^{-2}, \quad \text{and} \\
h_u &= 100\ \text{m},
\end{aligned}
$$

a transport of 40,000 m^3 sec^{-1} is found which compares well with a net average of 56,000 m^3 sec^{-1} calculated from our direct current measurements. During periods of high inflow such as that seen on 19–25 April 1972 (Figure 5), we found a thickness of 150 m and a width of 6×10^3 m. Using these values we calculated a transport of 94,000 m^3 sec^{-1}, which is in good agreement with the flow of 99,000 m^3 sec^{-1} determined from direct current measurements made on April 24. Whitehead *et al* show photographs (their Figure 5) of flow over a spillway at several speeds of rotation which resemble the character of the flow depicted in our Figure 3.

It is apparent from a comparison of Figures 4A and B that each depicts a different circulation pattern near the Jungfern Sill. The distribution of the cold silica-poor Atlantic water in Figure 4A is interpreted to illustrate a situation wherein none of that water is entering the Caribbean. The flow at the sill at this time may either be practically zero or in the direction of the Atlantic at low speed. The maximum incursion of the cold plume into the Venezuelan Basin, shown in Figure 4B, represents a period of strong inflow. The velocity and duration of the flow over the sill as measured by anchored current meters corroborate these interpretations of the STD and silicate measurements.

The shape of the plume and its relation to the isobaths shows that this dense layer does not flow directly down the steep slope into the basin. In the vicinity of the sill, the current direction seems to be controlled by the shape and orientation of the channel, but once inside the basin the tongue of inflowing water shows a tendency to follow the isobaths keeping the shallow water on the right. From April 20–25 the single current meter still measuring speed and direction recorded relatively constant velocities, and the STD data show that the dimensions of the plume were essentially unchanged. Since neither the transport nor the size of the plume appeared to change during this period it is likely that an equilibrium between inflow and mixing had been reached.

The question arises as to whether the flow of cold silica-poor Atlantic water into the Caribbean is accomplished as a series of pulses sending discreet boluses drifting across the Caribbean Sea, or if the plumes of water shown by the STD observations are being steadily eroded away along the leading edge through intense mixing as the cold water flows downslope into the Venezuelan Basin while simultaneously being renewed by inflow over the Jungfern Sill. If the latter alternative is the case, variations in the velocity of the flow and the thickness of the layer of renewal water could be expected to result in corresponding variations in the volume of the plume and the location of the leading edge. This is consistent with the evidence. The STD observations show a cold plume within the Venezuelan Basin of an estimated 1.4×10^9 m^3 during the period from 18 to 25 April 1972 (Figure 4B). During this same period, the current meter records indicate an average transport of Atlantic water into the basin of 90×10^3 m^3 sec^{-1}, a flow sufficient to replace the plume every 4.3 hours. During periods of outflow at the Jungfern Sill, the cold water disappears entirely from the south side of the sill and is found only below sill depth on the north side (Figure 4A).

D. K. Atwood (personal communication) states that a serial hydrographic station occupied every three months since 1971 about 40 km south of the southwest corner of Puerto Rico frequently shows faintly anomalous temperature and silicate values near a depth of 2,000 m. Sturges (1970) finds an intermediate temperature minimum in some eastern Caribbean stations occupied in 1966 by Worthington (1971) that he believes owes its origin to inflow over the Jungfern Sill. He believes that as the flow cascades downslope, it entrains basin water until a density balance is reached at a depth of approximately 2,450 m.

5. Direct current measurements

a. Previous work. The earliest current survey of the various passages through the arc of the Greater and Lesser Antilles was carried out and reported by Pillsbury (1891). He did not have very reliable bathymetric data in the vicinity of the sills, and very little information concerning the deep flow can be derived from his work.

In 1965, current meter moorings were anchored by the Soviet Research Vessel MIKHAIL LOMONOSOV for approximately one day in both the Windward and Anegada Passages (Sukhovey and Metal'nikov, 1968). The records from both passages show a net flow into the Caribbean between the surface and 600–700 m and a net flow out of the Caribbean below 700 m. The hydrographic station data listed by Metcalf *et al* (1973) show that at depths between 800 and 1700 m evidence of high silicate and low oxygen levels, clearly of Caribbean origin, is found in the Atlantic close to the entrance to the Anegada Passage. (See Metcalf *et al*, 1973, Figures 8 and 10.) Hydrographic stations occupied in this area in 1963 (Worthington, 1971) also show the influence of Caribbean water at the same depths, suggesting that deep outflow through this passage is not uncommon. This outflow sometimes extends down to sill depth (1815 m) as will be shown when our current meter data from the sill area are described below.

During February 1969, Sturges (1970) made a series of direct current measurements and STD stations in the area of the Jungfern Sill. He found that the rectifying effect of the sill on the strong semi-diurnal tidal component present in his records could result in a net transport of 6.4×10^3 m^3 sec^{-1} of dense Atlantic water into the Venezuelan Basin. Sturges also found a maximum current of 20 cm sec^{-1} flowing into the Caribbean during one eleven hour surge. The average transport during this period was 50×10^3 m^3 sec^{-1}, and he states that the transport could be increased by a factor of four if the thickness of the inflowing layer were doubled. According to Sturges's calculation, a flow of 100×10^3 m^3 sec^{-1} would be sufficient to offset the heat flux through the bottom and the oxygen consumption rates, thus giving steady state heat and oxygen budgets in the deep Caribbean.

Further measurements made in February 1971 were reported by Sturges (1975) as showing essentially similar results. They showed cold Atlantic water at depths as shallow as 1600 m, and the current appeared to be in geostrophic balance. Instead of flowing directly downslope into the Venezuelan Basin, the current was found to turn to the right and flow about 20° to the left of the isobaths.

b. Present study. The placement of the current meter array on the Jungfern Sill and the spacing of the instruments in each mooring was determined largely on the basis of Sturges's (1971) preliminary results which show inflowing water passing over the sill in a relatively thin (50 m) layer only 5–6 km wide. An array of four current meters (Richardson, Stimson and Wilkins, 1963) in two subsurface moorings similar to those described by Stalcup and Metcalf (1972) were placed on the Jungfern Sill on March 18 and retrieved on April 25, 1972. Figure 1 shows the positions of these moorings. One mooring was set in 1760 m of water at the western side of the passage across the sill (17°35.6′N, 65°15.2′W) and the other was set near the center of the sill itself in 1810 m of water (17°35.5′N, 65°14.5′W). At each mooring, the lower instrument was 8 m and the upper one 58 m above the bottom. In addition to recording 14 measurements of current speed and direction during a one minute period at 7.5 minute intervals, the instruments also recorded one temperature measurement every 7.5 minutes.

Although three of the four current meters had malfunctions, some information was gained from each instrument. Only one complete current-temperature record

Table 1. Summary of current meter and temperature records.

			Record Length (days)			
	Inst. #	Depth	Temp.	Speed	Dir.	Location
Shallow............ (58 m above the bottom)	4261	1702 m	37	37	0	Western edge of sill
Deep.............. (8 m above the bottom)	4262	1752 m	6.5	6.5	6.5	Western edge of sill
Shallow............ (58 m above the bottom)	4271	1752 m	37	26	26	Center of sill
Deep.............. (8 m above the bottom)	4272	1802 m	37	37	37	Center of sill

was obtained but fortunately this record was from the deep meter (# 4272) anchored near the center of the sill where it was in the best position to monitor the inflow. From the upper meter (# 4271) in this mooring, the temperature record is complete, but currents were measured only until April 14. In the mooring at the western edge of the sill the lower instrument (# 4262) recorded currents and temperatures for only 6.5 days before the magnetic tape transport mechanism failed. The shallow instrument (# 4261) at this mooring recorded temperature and speed but not direction throughout the entire experiment. The performance records of these instruments are listed in Table 1.

In spite of these failures the data have provided us with an insight into the character of the circulation over this sill that is possible only with records of this type. The temporal and spatial differences in the temperature data show good correlation with the current speed and direction and thus permit inferences to be made of the current direction and, to some extent, the current speed from the temperature records alone. This correlation was especially useful during the analysis of record # 4261 in which direction was not recorded.

An instability in the flotation unit of mooring # 427 resulted in an oscillation of the float that introduced "noise" in the record of the current meter (# 4271) directly beneath this float. This problem has occured before and, with the data reduction techniques routinely employed at WHOI, can affect the results of the data analysis. To illustrate this problem two progressive vector diagrams have been constructed from these data and are shown in Figure 5. The shorter of the two vector summations is the result of using vector averaging to process the data. This method of averaging current meter data which has been contaminated by "noise" from an oscillating float results in lower velocities and a clockwise rotation of the directions. (See Stalcup and Metcalf, 1972, for an explanation of this problem.) The longer of the two vector summaries for record # 4271 was constructed from numerically averaged speeds to reduce the effect of the mooring motion and is, we believe, the more accurate of the two presentations.

6. Results

The progressive vector summations shown in Figure 5 were constructed with hourly averages except where 15 minute averages were used to show greater detail during a period of outflow. Only the record from # 4272 is continuous from March 18, when the current meters were moored, to April 25 when they were recovered. This record shows a predominent flow toward the southwest with an average velocity of 20 cm sec^{-1}. The most obvious feature is the current reversal from April 8–13 enlarged in the inset of Figure 5 to show both the slower and more variable velocities during this period and the net northeast flow. Although the progressive vector summations for both # 4271 and # 4272 are similar, the current reversal begins at a different time in each record. At the shallow meter the reversal begins on April 4 while at the meter 50 m deeper at the same mooring it does not begin until April 8. This difference results from a reduction in the cross-sectional area of the current as it begins to slacken prior to April 4. Since the shallow meter is closer to the top of the plume than is the deep meter, it is the first to record the effects of a reduction in velocity accompanying the shrinkage of the plume. First this meter and finally both of them record northeast flow until April 14 where the upper current record stops. If it is true that changes in the dimensions of the plume correspond to changes in velocity one might expect the inflow to recommence first at the deep meter and later at the shallow meter. The velocity record from the shallow meter ends on April 14 but the temperature record shows a sharp decrease on the 16th, three days after a similar decrease in temperature at the deep meter. We interpret this to indicate that the inflow of cold Atlantic water at the shallow meter was delayed an equal time, and that the dimensions of the plume are therefore related to the velocity. Weak inflow produces a thinner and probably narrower plume of cold water in the Venezuelan Basin than does strong inflow, and the absence of a plume over the sill probably accompanies outflow, or at least a lack of inflow.

The kinetic energy density spectra for current meter records # 4262, 4271 and 4272 are shown in Figure 6. A prominent peak at about 12.5 hours represents a semi-diurnal tidal component in each record. Numbers 4271 and 4272 also show a diurnal tidal peak at about 25 hours. Record # 4262 was too short to show this peak clearly. Recent work by Hansen (1974) indicates that there may be normal modes of oscillation (seiches) within the Caribbean at periods of 16.0, 8.0, 6.8, 6.1, 4.5 and 3.2 hours, but the general "noise" in the records makes it unclear as to whether or not this is what we are seeing. The high kinetic density at high frequencies in # 4271 is thought to be due to the oscillatory rotary motion of this float transmitted to the current meter as was discussed earlier.

The relationship between the potential temperature and the current at two levels at the center of the Jungfern Sill is shown in Figure 7A and B. The current is given in centimeters per second in terms of the component in the direction of 210° True. That is, positive speeds are directed into the Caribbean and negative speeds out of it (030° True). The situations at the two levels are essentially the same with the lowest temperatures associated with the strongest inflow and the higher temperatures with weak inflow or actual outflow. Each dot in the scatter diagrams represents the average of the 112 individual current measurements and the 8 temperature measurements recorded each hour. In the case of instrument # 4271 which was 58 m above the bottom (Figure 7A) the complete temperature-current record was only 26 days long due to a malfunction in the current meter. The temperature recorder continued to function properly for the remaining 11 days of the study. The correlation between temperature and current shown in the diagram indicates that much information concerning the current can be deduced from the temperature record alone.

The various clusters of dots in the diagrams reveal certain characteristics of the current. In the case of record # 4272 (Figure 7B) the very large number of dots loosely clustered in the upper left corner of the diagram indicates that the predominant current condition 8 m above the bottom was one of strong inflow and low temperatures. Fifty meters above this in the same water column (Figure 7A) the balance between inflow and outflow (cold and warm) is more even. The potential temperature readings are especially closely concentrated between 3.95 and 4.00°C when nearly isothermal Venezuelan Basin water is flowing past the current meters during periods of outflow. In both diagrams there are areas with very few dots indicating conditions which are present only fleetingly as the currents change from positive to negative (cooler to warmer temperatures).

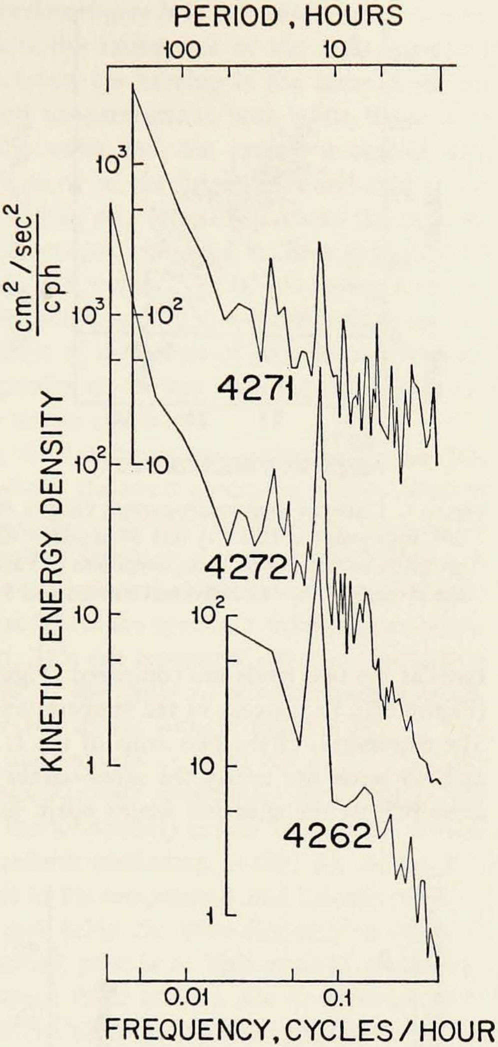

Figure 6. Kinetic energy density diagrams of three current meter records from the Jungfern Passage, March–April 1972. Note the strong semidiurnal peak along with the pronounced diurnal and 6.8 hour peaks. The high frequency "noise" in the upper record (# 4271) is due to excessive oscillation in the mooring float (see text).

A second set of scatter diagrams was constructed in which the potential tempera-

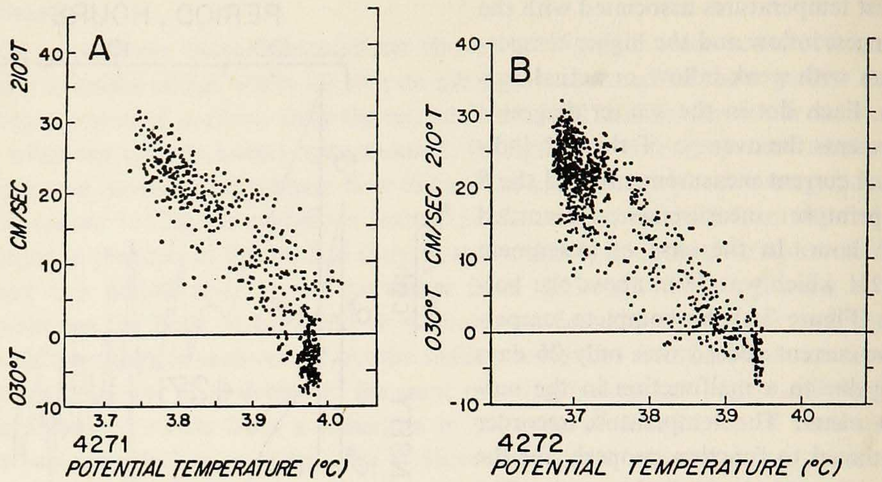

Figure 7. Potential temperature-current velocity relationship at the center of the Jungfern Passage Sill. Instrument # 4271 (A) was 58 m and # 4272 (B) was 8 m above the bottom. The currents are given in terms of the component into (+) and out of (−) the Caribbean. Each dot represents the average of the 112 individual current and 8 temperature measurements recorded each hour.

tures at the two levels are compared (Figure 8A) as are the currents at those levels (Figure 8B). In the case of the temperatures, a distinctive L-shaped pattern appears. The extremities of the two arms of the L reflect situations where the temperatures at both levels are nearly the same—either warm or cold. The junction of the two arms reflects the situation where warm temperatures are present at the shallower

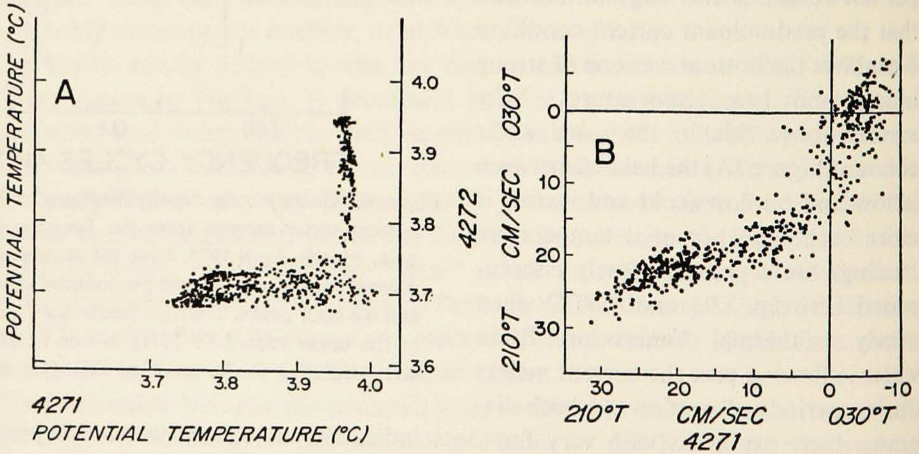

Figure 8. The potential temperatures at 58 and 8 m above the bottom (A) and currents at those levels (B) are compared. The instruments are the same two that are treated in Figure 7, and the current component and the hourly averaging process are as described for that Figure.

level and cold at the deeper. From the previous figure it is seen that there is a close temperature-current relationship, and thus the extremities of the arms represent conditions wherein the currents at both levels are moving in the same direction. That is, at the end of the arm showing low temperatures at both levels, the current is moving into the Caribbean, and at the warm end, the current is coming out. At the junction of the arms, the water is warm at the upper level and cold at the lower implying outflow 58 m above the bottom and inflow 8 m above the bottom. As would be expected from density considerations, there are no data points in the area representing warm water underlying cold water. This is in keeping with the current regime described earlier in which the changes in current directions are accompanied by the expansion and contraction of the plume of Atlantic water which hugs the bottom in the sill area. Consequently, at no time does the water flow out at the deeper level while it is flowing in at the shallower.

The diagram in which the currents at the two levels are compared (Figure 8B) gives a much less dramatic pattern but shows the same general situation. Most of the dots fall in the quadrant representing inflow (positive speeds) at both levels. A lesser concentration of dots shows outflow (negative speeds) at both levels. A third category of dots falls in the quadrant representing outflow at the shallower level and inflow at the deeper. Only one dot falls in the quadrant representing outflow at the lower level and inflow at the upper. This dot represents very slow movement (1–2 cm sec^{-1}) at either level, and considering the range of scatter expected in observations of this type, it is considered to be entirely without significance.

Temporal changes in the temperature and velocity or speed for each record are shown in Figure 9A–D. The records all show certain similarities: each shows a net transport to the southwest (inflow into the Caribbean) except for record # 4261 which lacks directional data, and all the records (excluding # 4262 which was only 6 days long) show the same general trends in the temperature and current patterns. In the two shallower records (# 4261 and 4271) the semi-diurnal periodicity is marked by especially wide fluctuations during periods of high average speeds and low average temperatures. Apparently during these periods, the instruments 58 m above the bottom were near the depth of the sharp temperature gradient marking the interface between the cold Atlantic and the warmer Venezuelan Basin water (see Figure 3).

7. Interpretation of the data

Based on STD and current meter data, and using the pair of current meters and temperature recorders anchored near the middle of the Jungfern Sill to illustrate the situation, the movement of water over the sill is described as follows. The reader may wish to refer to Figure 9C and D in following this description. Starting arbitrarily during a period of outflow from the Caribbean and with warm Venezuelan Basin water present right to the bottom on the sill (12 April) the current records for both levels show small but marked semi-diurnal tidal signatures while the temperature

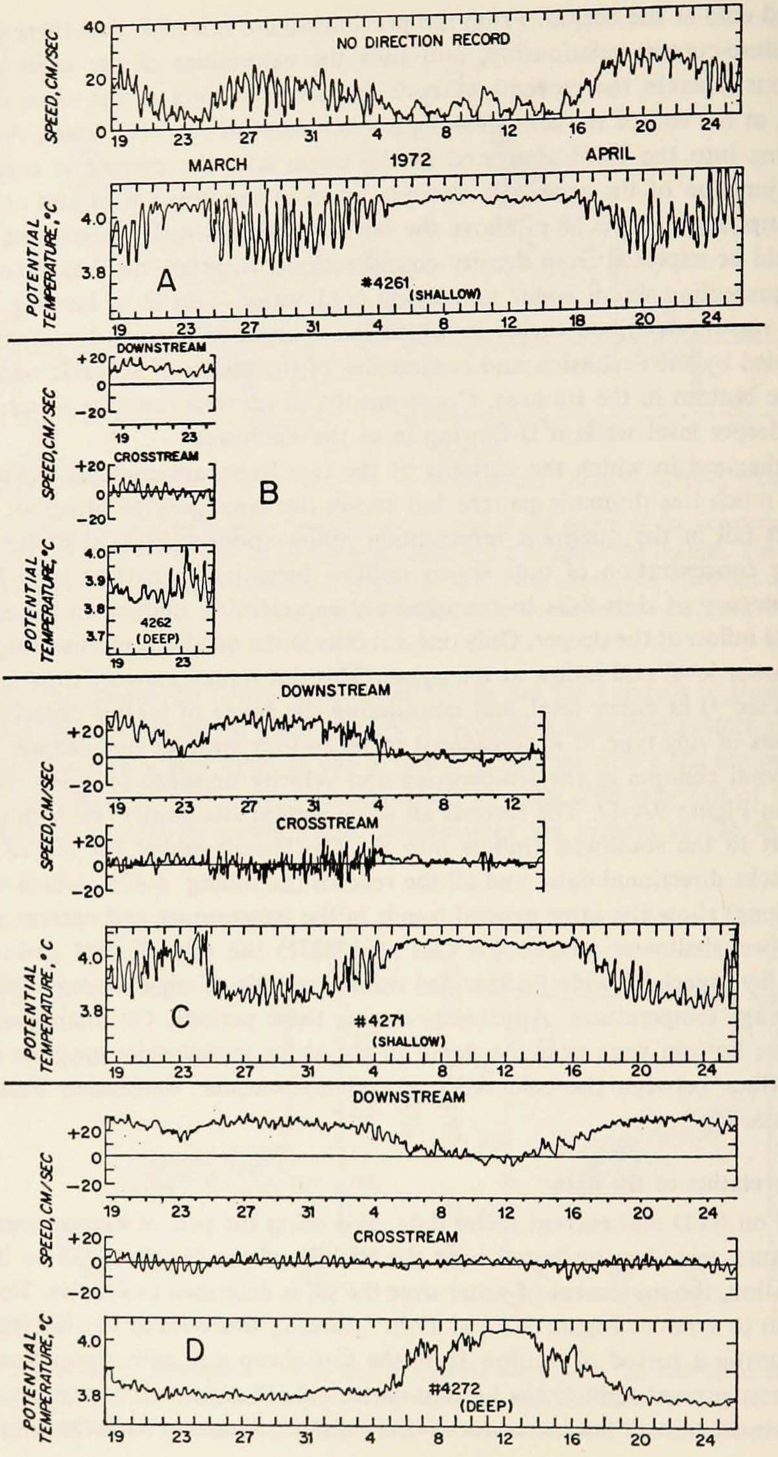
SPEED, CM/SEC
40
20
0
NO DIRECTION RECORD
19 23 27 31 4 8 12 16 20 24
MARCH 1972 APRIL
POTENTIAL TEMPERATURE, °C
4.0
3.8
A
#4261
(SHALLOW)
19 23 27 31 4 8 12 18 20 24
DOWNSTREAM
+20
0
−20
19 23
CROSSTREAM
B
4.0
3.9
3.8
3.7
4262
(DEEP)
19 23
DOWNSTREAM
19 23 27 31 4 8 12
CROSSTREAM
C
#4271
(SHALLOW)
19 23 27 31 4 8 12 16 20 24
DOWNSTREAM
CROSSTREAM
D
#4272
(DEEP)
19 23 27 31 4 8 12 16 20 24

Figure 9.

records show relatively little fluctuation. Gradually a thin layer of cold Atlantic water begins to move towards the Caribbean along the bottom near the deepest part of the sill. As the thickness of this layer increases the small but sharp thermal gradient at the interface between the Atlantic and Venezuelan Basin waters reaches the level of the deep current meter 8 m above the bottom, and the tidal pulses accompanying the movement make themselves evident as wide fluctuations in the temperature (14 April). At this time the instrument 58 m above the bottom is still experiencing relatively little temperature fluctuations, being still immersed in the warm Caribbean outflow.

The plume of cold water continues to increase in thickness, and the gradient between the two layers reaches the level of the upper current meter which now (16 April) records wide temperature fluctuations. At this same time, the lower record ceases to show widely fluctuating temperatures as that instrument becomes surrounded by the cold Atlantic water. The tidal pulses in the current at the deeper level continue without much change in magnitude, but the movement becomes one of net inflow. As the cold plume continues to enlarge, the Atlantic water reaches the upper instrument where the outflow now also becomes an inflow and the tidal signature in the temperature record becomes more pronounced (18 April). The record of current direction for this instrument ceases about this time, but the current reversal accompanying the cooler water may be inferred from the relatively straightforward temperature-current correlation shown in Figure 7A.

On an occasion near the beginning of the record (22–24 March) the plume became somewhat thinner so that the temperature at the upper instrument rose markedly amidst much tidal fluctuation, and the inflow subsided to virtually nothing. This trend soon reversed itself without affecting the lower instrument to any significant extent. Shortly after this (26 March) the plume reached a thickness great enough so that the sharpest part of the interface thermal gradient was a little above the upper instrument with the effect that the temperature fluctuation of the tidal period was slightly reduced from its maximum. It still remained quite large, however, indicating that the lower part of the sharp gradient was still close to the instrument 58 m above the bottom. During this period of maximum inflow, the average velocity was about 25 cm $\sec^{-1}$, and the temperature near the bottom went as low as 3.77°C (a potential temperature of about 3.62°).

According to our interpretation, the inflow begins to slacken first near the edges of the plume where it is eventually replaced by outflow, but the failures of instruments # 4261 and 4262 make this difficult to verify. Finally the inflow across the Jungfern Sill ceases completely, and the outflow is probably continuous throughout the layer

Figure 9. Potential temperature and current records from the Jungfern Sill. Instruments # 4261 (A) and 4262 (B) were 2 km west of the center of the sill. Numbers 4271 (C) and 4272 (D) were very close to the center (see Figure 1). Direction was not recorded by # 4261 (A). In all other cases, positive downstream speeds are 210° True (Caribbean inflow) and negative speeds are 030° True (outflow). Cross-stream components are 300° T (+) and 120° T (–).

we have been describing. Just how thick this layer might be is not disclosed by the present data. Sukhovey and Metal'nikov (1968) have reported that in the Anegada Passage, the outflow may extend from a depth of 700 m all the way to the bottom. It should be emphasized that our sequence described here is based on only a little over one lunar cycle of data and may not represent average conditions over a longer period. However, this is an appreciably longer series of observations than any made previously.

During the period studied, the deep flow through the Jungfern Passage was toward the southwest and consisted of Atlantic water with the following characteristics: $t_p = 3.68°C$, $S = 34.98‰$, $O_2 = 6$ ml/l, and $SiO_2 = 17$ μg-atoms/l. This current occasionally stopped and permitted Caribbean water with the characteristics $t_p = 3.95°C$, $S = 34.97‰$, $O_2 = 5$ ml/l and $SiO_2 = 28$ μg-atoms/l to flow into the Atlantic. However, the average net transport was into the Venezuelan Basin at approximately 56×10^3 m^3 sec^{-1}. Sturges (1970) using rough order-of-magnitude estimates of the heat and oxygen fluxes, calculated that a renewal rate of about 100×10^3 m^3 sec^{-1} would maintain the present temperature and oxygen levels in the Caribbean. Our figure of 56×10^3 m^3 sec^{-1} is thus well within the limits Sturges claims for the accuracy of his calculations. Very little is known about the Caribbean silicate budget, but it is possible that a steady state condition does not exist at present with regard to silicate.

Models of the transport and character of flow over a sill such as that found in the Jungfern Passage predict the rapid mixing near the sill that is seen in the present data. The absence of an easily identifiable layer of Atlantic water within the Venezuelan Basin beyond a few kilometers from the sill is undoubtedly the result of this intense mixing.

During periods of maximum inflow in our observations the cold water in the sill area was in the shape of a plume 5 km wide, somewhat more than 58 m thick extending about 8 km beyond the sill into the Venezuelan Basin. These dimensions changed little during such periods. However, when the current slackens, the size of the plume is reduced so that the sensors near the margins show a shorter period of inflow than is found near the center of the passage. Measurements near the axis of the current show long periods of inflow into the Caribbean separated by short periods of outflow. The STD data indicate that the current in the Jungfern Passage is strongly confined by the bathymetry of the passage. Thus changes in the current as measured by the current meters anchored in the channel are not attributable to lateral displacements of the current but reflect alternations in the structure of the current.

Acknowledgements. This research was supported by the National Science Foundation under Grant GA 27939. The authors wish to express their thanks to Dr. Wilton Sturges who made many helpful suggestions for carrying out the bathymetric and STD surveys based on his own work in the area of the Jungfern Sill. The deployment and recovery of the current meters and the reduction of these data were carried out by members of the WHOI Buoy Group supported by contract N00014-66-C0241, NR 083–004 with the Office of Naval Research.

REFERENCES

Frasetto, R. and J. Northrup. 1957. Virgin Islands bathymetric survey. Deep Sea Res., 4: 138–146.

Grasshoff, K. 1964. On the determination of silica in sea water. Deep Sea Res., 11: 597–604.

Hansen, Kirk S. 1974. Calculations of normal modes for the American Mediterranean Seas. Master's Thesis, Dept. Geophys. Sci., University of Chicago, August.

Metcalf, W. G., M. C. Stalcup and M. E. Zemanovic. 1971. Hydrographic station data from ATLANTIS II Cruise 56 to the southeastern approaches to the Caribbean Sea, February–April 1970. Woods Hole Ocean. Inst. Ref. 71–13, 179 pp. (unpublished manuscript).

Metcalf, W. G., M. C. Stalcup and M. Zemanovic. 1973. Hydrographic station data, Caribbean Sea, KNORR Cruise 25. Woods Hole Ocean. Inst. Ref. 73–10, 135 pp. (unpublished manuscript).

Pillsbury, J. E. 1890. The Gulf Stream, methods of the investigation and results of the research. U.S. Coast and Geodetic Survey Rep. 1890, append. 10, Gov. Printing Off., Wash., D.C.

Richards, F. A. 1958. Dissolved silicate and related properties of some western North Atlantic and Caribbean waters. J. Mar. Res., 17: 449–465.

Richardson, W. S., P. B. Stimson and C. H. Wilkins. 1963. Current measurements from moored buoys. Deep Sea Res., 10, (4): 369–388.

Richardson, W. S., A. R. Carr and H. J. White. 1969. Description of a freely dropped instrument for measuring current velocity. J. Mar. Res., 27, (1): 153–157.

Ross, C. K. and C. R. Mann. 1971. Oceanographic observations in the Jungfern Passage and over the sill into the Venezuelan Basin, February, 1968. Symposium on Investigations and Resources of the Caribbean Sea and Adjacent Regions, Curacao, 1968, UNESCO, Paris, pp. 171–174.

Schleicher, K. E. and A. Bradshaw. 1956. A conductivity bridge for measurement of the salinity in sea water. J. du Cons. 22, (1): 9–20.

Stalcup, M. C. and W. G. Metcalf. 1972. Current Measurements in the Passages of the Lesser Antilles. J. Geophys. Res., 77, (6): 1032–1049.

Stalcup, M. C. and W. G. Metcalf. 1973. Bathymetry of the Sills for the Venezuela and Virgin Islands Basins, Deep Sea Res. 20, (8): 739–742.

Sturges, Wilton. 1970. Observations of Deep-Water Renewal in the Caribbean Sea. J. Geophys. Res. 75, (36): 7602–7610.

Sturges, Wilton. 1975. Mixing of renewal water flowing into the Caribbean Sea. J. Mar. Res. Supl. 33: 117–130.

Sukhovey, V. F. and A. P. Metal'nikov. 1968. The deep-sea water exchange between the Caribbean Sea and Atlantic Ocean. Oceanology, 8: 159–164.

Whitehead, J. A., A. Leetma and R. H. Knox. 1974. Rotating hydraulics of strait and sill flows. Geophysical Fluid Dynamics 6: 101–125.

Worthington, L. V. 1966. Recent oceanographic measurements in the Caribbean Sea. Deep Sea Res., 13, (4): 731–739.

Worthington, L. V. 1971. Water circulation in the Caribbean Sea and its relationship to the North Atlantic Circulation. Symposium on Investigations and Resources of the Caribbean Sea and Adjacent Regions, Curacao, 1968, UNESCO, Paris, pp. 181–191.

Received: *11 November, 1974*; revised: *26 December, 1974*. WHOI Contribution No. 3430.