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On the currents and water masses north of the Antilles/Bahamas arc

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ABSTRACT

The Antilles Current, which is supposed to flow from the Atlantic North Equatorial Current along the Antilles and Bahamas island arc and contribute to the Gulf Stream, does not always exist. Data from the two most extensive grids of hydrographic surveys yet available in this region, one in summer and one in winter, show that mesoscale eddies dominate the baroclinic current field and the distribution of water properties. Earlier works based upon individual sections and more limited data have likely been misled by such eddies. Water property gradients along density surfaces in this region are sufficiently large throughout the upper 1000 m to trace the flow, when it exists, along the Antilles in both surveys. The flow patterns so deduced substantiate the baroclinic current field derived from dynamic calculations. The winter survey shows a net northwestward transport of 9×10^6 m^3 sec^{-1}, and a tongue of Subtropical Underwater indicates that the current had persisted for at least two months, based upon an advective time scale. Conversely, the summer survey shows no net northwestward transport, and the persistence of its absence is indicated by the lack of any alongshore water property tongues. The increased northward flow at the western boundary in the winter is consistent with seasonal variation in southward Sverdrup transport calculated from the wind stress curl at this latitude across the North Atlantic, but NODC historical data are insufficient to indicate whether the Antilles Current may exist seasonally.

The summer survey reveals a strong flow into the Windward Passage, with transport estimated to be $15 \pm 5 \times 10^6$ m^3 s^{-1}, corroborated by the distribution of Antarctic Intermediate Water (at 1000 m). Historical hydrographic data from NODC, for the regions leading toward and within the Windward Passage, suggest a seasonal pattern of the flow of AAIW through the passage, present in the fall and winter but not in the spring.

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1. Introduction

In the North Atlantic subtropical gyre, the traditional picture shows a bifurcation of the North Equatorial current. One portion flows into the Caribbean, and the rest flows northwestward along the Antilles/Bahamas archipelago, eventually contributing to the transport of the Gulf Stream. Previous investigations in this region have produced disagreement regarding the steady presence of this northwestward current.

In this paper we analyze the results from two surveys of the region through which the Antilles Current is supposed to flow. The surveys, which were made by the National Marine Fisheries Service in the summer 1972 and the following winter 1973, each present a synoptic description of the regional hydrography. They constitute the most extensive data sets yet collected there. By examining the baroclinic transport and the advection of different water properties, we find the currents to be highly variable. In the winter survey there is a net northwestward transport and advection, but not in the summer, and both surveys have eddy-dominated current fields.

The time-dependent existence of an Antilles Current is discussed in the context of broader regional variability, in order to investigate whether it may be part of a seasonal pattern. In particular the transport through the Florida Straits has a seasonal dependence, and the seasonal variation of Sverdrup transport is shown. Moreover, by investigating historical NODC hydrographic files we deduce a seasonal variation in the flow of Antarctic Intermediate Water through the Windward Passage. A seasonal pattern for the regional currents is speculatively summarized in the concluding section.

2. Previous literature

For many years the concept has persisted of a well-defined northwestward flow along the Antilles/Bahamas arc (Wüst, 1924; Iselin, 1936), however there has been disagreement on the steady nature of the current and the amount of volume transport contributed to the Gulf Stream. Recent transects across this region (Ingham, 1975; Amos *et al.*, 1971) show a current regime with significant variation both in space and time. Moreover, the smooth increase in the volume transport of the Gulf Stream between the Florida Straits and Cape Hatteras (Knauss, 1969) gives little evidence of a steadily present Antilles Current. Worthington's (1976) general scheme for the North Atlantic circulation does not require an Antilles Current but relies on a recirculation gyre farther north to increase the transport of the Gulf Stream.

The fact that different investigators present conflicting concepts of an Antilles Current undoubtedly arises because they have been observing a time-varying eddy-dominated field. Investigations of the Antilles Current using current meters (Costin,

Table 1. STD station summary.

Cruise	Dates	# Stations	Meridional # sections	Spacing	Region
"summer"	7-8/72	74	9	100 km meridional 100-300 km zonal	61-81 W 18-30 N
"winter"	1-2/73	55	7	50-100 km meridional 100-200 km zonal	71-78 W 20-32 N

1968; Maloney, 1968) and others using hydrographic data (Day, 1954; Kort, 1972), have been too limited in duration or spatial resolution to be unbiased by the eddy field.

3. New observations

The data for this study were collected by the National Marine Fisheries Service during the MARMAP[3] program aboard the R/V *Albatross IV* in July-August 1972 and January-February 1973, henceforth referred to as the "summer" and "winter" cruises. The survey regions overlapped, as summarized in Table 1. The winter cruise extended farther north, the summer cruise farther east. These surveys have provided the most extensive, synoptic data set yet collected in the Atlantic off the Antilles.

Continuous STD profiles, including oxygen content in the winter, were taken at the grid points indicated in Figures 2 and 3. Most stations were 1000 m deep, with reversing thermometers and water samples at representative depths to confirm the STD performance. Gunn (1979) reviewed these observations in more detail.

Additionally, XBT profiles were taken at each STD and halfway between stations along meridional sections. Although the XBT's are not explicitly discussed in this paper, it is significant to note that *all features of the circulation have confirmation in the finer grid XBT survey*.

In this study we analyze the STD data by standard techniques (the dynamic method) and examine the advection of cores of anomalous water properties in order to deduce the flow. The baroclinic current profiles and transports are subject to the usual caveats regarding how representative of the longer term mean flow they may be, and regarding uncertain reference velocities. The 1000 m depth limitation imposes considerable uncertainty on the transport values. Errors in temperature and salinity may contribute transport uncertainties of 10^6 m^3 sec^{-1}, however the uncertainty due to a non-zero reference velocity at 1000 m may be an order of magnitude larger.

Fortunately, in this geographic region, contributions from several water masses exist, with distinctly recognizable T-S and/or oxygen signatures. By examining and

3. Marine Resources Monitoring, Assessment and Prediction, Operational Test Phases I and II.

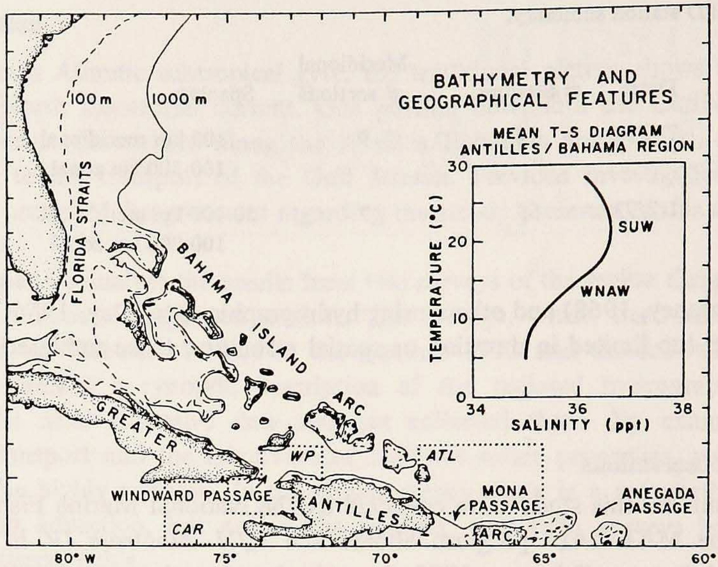


Figure 1. Geography of the study area, including the 100 m and 1000 m isobaths. A specific localized study within the dotted regions "WP," "ATL" and "CAR," is discussed in the text. The inset shows the general TS characteristics of waters found all along the island arc. Centered near 6.5°C a local salinity minimum associated with Antarctic Intermediate Water may be present or absent depending upon location along the arc (see text).

tracking tongues of anomalous water properties we take advantage of indications that flow persisted long enough to advect the unique properties to new locations—the tracer field has "memory." A corollary argument applies in this region: the absence of advective features in the water property fields indicates the absence of organized, persistent currents through the region because it is bordered by waters whose core anomalies are large.

4. Water masses

Four characteristic features aid in the identification of water masses in the upper 1000 m east of the Bahamas and north of the Antilles. These are, in order down the water column: Subtropical Underwater, Subtropical Mode Water, an oxygen minimum and Antarctic Intermediate Water. The inset on Figure 1 shows the characteristic T-S diagram for this region (Gunn, 1979).

Below the surface waters the salinity increases to a maximum in the water column. This usually occurs between depths of 100 to 200 meters and identifies the core of the Subtropical Underwater (SUW). This water mass is formed in a region to the east, where evaporation exceeds precipitation (Worthington, 1976). Variations in precipitation, evaporation and mixing with other water masses can vary the amount of SUW produced. Despite this variability, the core of the SUW is a convenient and reliable indicator of persistent upper level circulation, observable at all stations in the studied region.

Below the SUW the vertical gradients of temperature and salinity decrease, characteristic of Subtropical Mode Water, STMW (Masuzawa, 1969; Worthington, 1959). In the North Atlantic this water type is associated with a thermostad close to 18°C and has been known as "18° water." The T-S characteristics of this water type in the North Atlantic are well documented (17.9 ± 0.3°C and 36.5 ± 0.10‰). The existence of a strong northwestward Antilles Current with a shallow thermocline to its left could inhibit STMW from entering the Caribbean through these passages. However, Worthington (1959) reports a concentration of this water type just west of the Windward Passage greater than anywhere else in the Caribbean suggesting a flow through this passage, at least part of the time. An occasional weakening or lack of an Antilles Current could enhance such flow.

Oxygen values below the STMW usually decrease to a minimum above the oxygen rich deep water. The presence of this oxygen minimum is a common feature in the deep main thermocline of the world's oceans. In the area of interest, the minimum occurs at approximately 800 m depth and consistently at the same sigma-t surface, 27.1 ± 0.1 (shown later on the inset of Figure 3c).

Below the oxygen minimum there is a salinity minimum that identifies the Antarctic Intermediate Water (AAIW). This water mass is also characterized by an increased oxygen concentration. AAIW is present in all parts of the South Atlantic and as far as 20N in the North Atlantic, north of which its distribution becomes fragmented.

5. The flow observed in the summer survey

The observations and the flow deduced from the summer cruise data are summarized in Figure 2. The distribution of the Subtropical Underwater (SUW) is displayed in Figure 2a, which contours the maximum value of the salinity in that layer. The strength of the salinity maximum decreases east to west from 37.1‰ along 61W longitude to slightly more than 36.5‰ west of 71W. The salinity maximum shows no extensive tongue-like distributions indicative of alongshore advection. Waters with a lower maximum in salinity (<36.65‰) extend north-south at 70-72W; otherwise mesoscale features dominate the near-surface flow.

Next lower in the water column is 18° water (STMW). To seek further indications of the circulation in the study area we present in Figure 2b a plot of the potential vorticity of the STMW layer. This quantity $\pi = (f + \xi)/H$ serves as a conservative tracer when non-adiabatic and viscous effects may be neglected; f and ξ are the vertical components of the planetary and relative vorticity, and H is the lens thickness delimited by the STMW properties noted earlier. We in fact approxi-

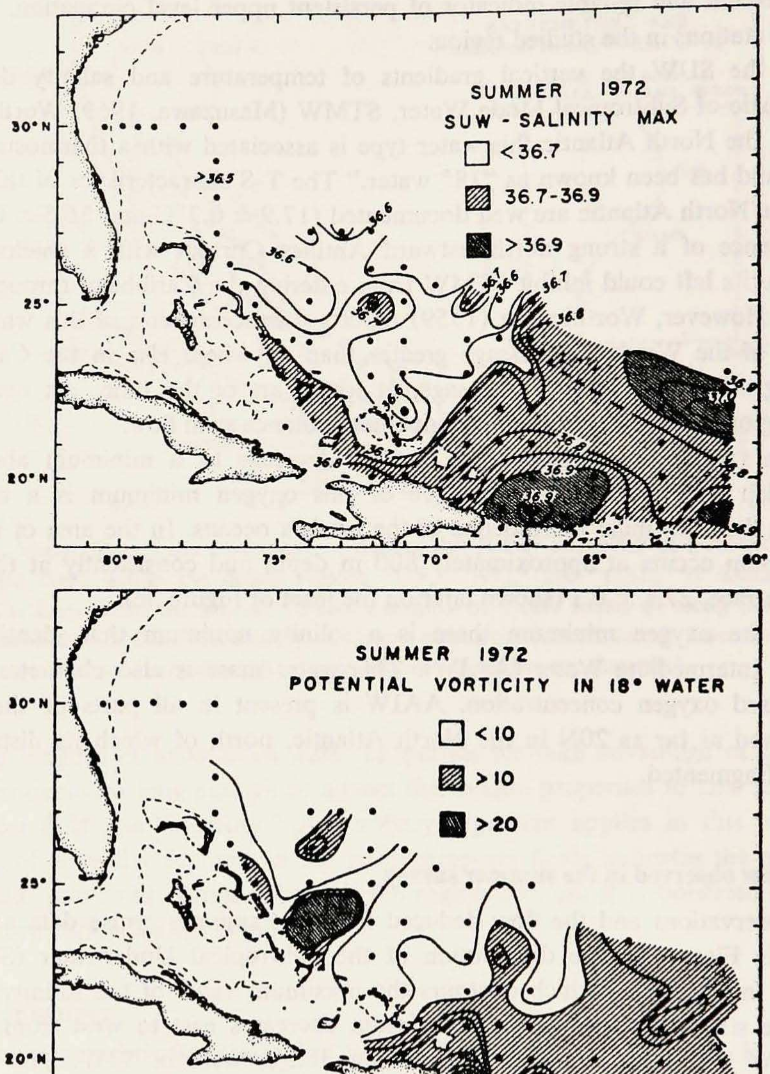
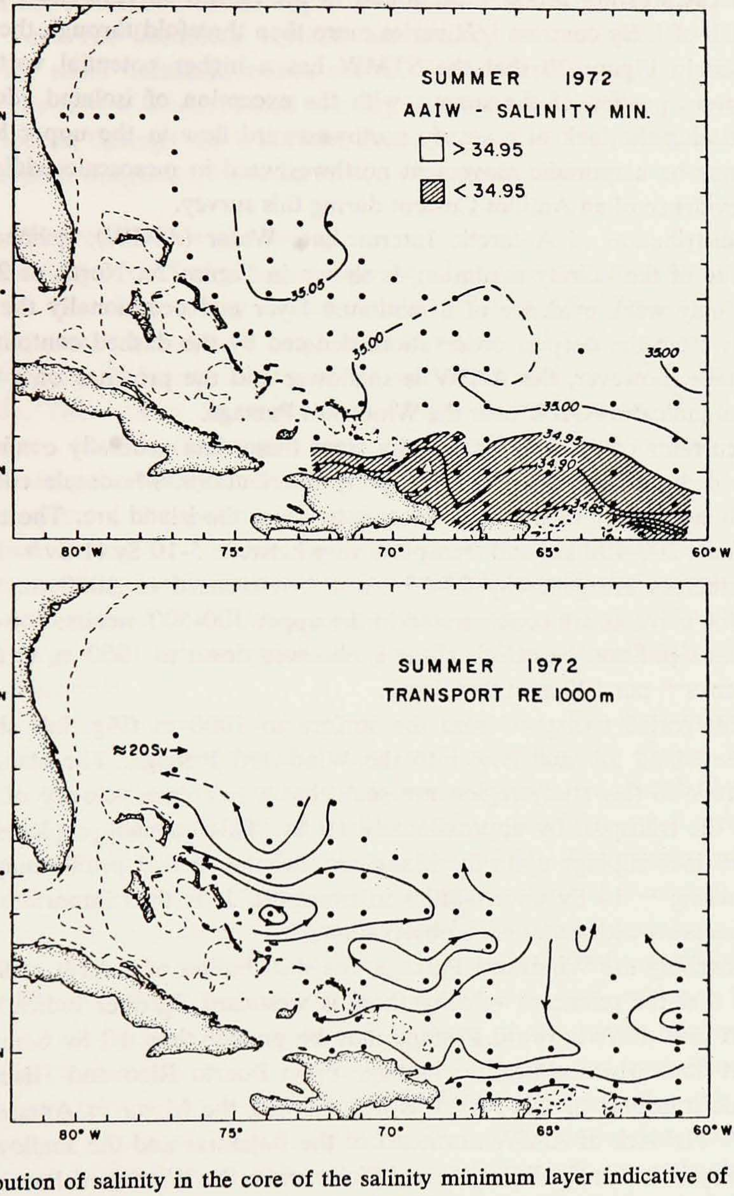


Figure 2. The NMFS summer survey. Dots denote station locations.

(a) Distribution of salinity in the core of the salinity maximum layer indicative of Subtropical Underwater (SUW). Contour interval is 0.05‰.

(b) Potential vorticity (10^{-7} m^{-1} s^{-1}) of water layer with TS characteristics of STMW (18° water).



(c) Distribution of salinity in the core of the salinity minimum layer indicative of Antarctic Intermediate Water AAIW. Contour interval is 0.05‰.

(d) Volume transport referenced to 1000 m. Each line represents a flow of 5 Sverdrups (1 Sv = 10^6 m^3 s^{-1}).

mate π by f/H in analyzing these data, because our estimate of ξ in even the most extreme cases of horizontal shear found in the NMFS surveys show it to be less than 10% of f. By contrast f/H varies more than threefold through the study area.

We see in Figure 2b that the STMW has a higher potential vorticity in the southeastern portion of the survey, with the exception of isolated eddies, further substantiating the lack of a steady northwestward flow in the upper level waters. There may be a sporadic movement northwestward in mesoscale eddies but there is little evidence of an Antilles Current during this survey.

The distribution of Antarctic Intermediate Water (AAIW), delineated by the core value of the salinity minimum, is shown in Figure 2c. North of 22N latitude there is only weak evidence of a minimum layer and occasionally the value used is merely from the deepest observation, denoted by the dashed contours. South of this latitude, however, the AAIW is shallower and the presence of a well-defined minimum indicates AAIW near the Windward Passage.

The currents calculated dynamically from these data generally confirm the flow patterns deduced from the water property distributions. Mesoscale eddies are the predominant feature of the circulation away from the island arc. The eddies range in size from 200-400 km and transports vary between 5-10 Sv (1 Sv $= 10^6$ m^3 s^{-1}). Peak velocities are generally 25-35 cm s^{-1} referenced to 1000 m. Outside the eddies, the currents are concentrated in the upper 300-500 meters, however, within the eddies significant baroclinic shear is observed down to 1000 m, at times reaching 3-4 cm s^{-1} per 100 m at that depth.

The integrated transport from the surface to 1000 m (Fig. 2d) shows eddies along the island arc and flow into the Windward Passage. The station spacings and latitude in this study region are such that a reference velocity of 10 cm s^{-1} changes the transport by approximately 10 Sv. This partially explains why some transport lines impinge upon the island arc, i.e. the current profile may deepen or shoal causing $\sim$ 10 Sv uncertainties in transport. It is thus important to confirm these transports with water mass observations.

Approaching the Windward Passage, the distribution of AAIW at 900-1000 m suggests that the reference velocity there is westward. Further indication that the transport into the Windward Passage may be greater than 10 Sv comes from the transport lines which appear to impinge upon Puerto Rico and Hispaniola. The baroclinic transport of this survey is not entering the Mona or Anegada-Jungfern Passage[4]. The lack of AAIW northeast of the Bahamas and the shallowness of the bathymetry between the Bahamas and Cuba make the Windward Passage the most likely path for this transport. The water property distributions (SUW, STMW, AAIW) support this description. Altogether, we estimate the flow into the Windward Passage to be $15 \pm 5 \times 10^6$ m^3 s^{-1}.

4. These passages are too small to accommodate a significant fraction of the transport. In the Anegada-Jungfern Passage (the deepest) Metcalf (1976) finds a net flow above 700 m of 2.2 Sv. The Mona Passage is smaller and only $\sim$ 405 m deep (H. O. chart 2318).

We summarize the results of the summer survey as follows: (a) Eddy variability characterizes the circulation of the upper level waters (<500 m depth) away from the Antilles Arc. The baroclinic currents are usually concentrated in the upper 500 m but for some locations, within eddies, the vertical shear is significant to 1000 m. (b) The AAIW is constrained to a region next to the Antilles Arc and flows into the Caribbean through the Windward Passage. (c) There is no evidence of an Antilles Current flowing northwestward to join with the Gulf Stream.

6. The flow observed in the winter survey

The circulation pattern had changed significantly in the region common to the two cruises for the winter survey as may be seen in Figure 3. The distribution of SUW (Fig. 3a) shows a tongue of high salinity water (>36.6‰) advected northwestward along the Bahamas Banks. It is well developed for 1000 km and is 200 km wide. The salinity decreases from 36.8‰ in the east to 36.6‰ at the western extreme. Outside the tongue there are no salinities greater than 36.65‰ except approaching the Windward Passage.

The distribution of the potential vorticity of STMW also contrasts with the situation found during the summer survey. Now there is a continuous band of high potential vorticity in the waters close to the Bahamas Banks, indicative of a persistent northwestward flow. There is also some mesoscale variability evident in water farther north, but the continuous nature of this band is strikingly similar to the SUW core above it.

Dissolved oxygen was measured during the winter cruise. The inset in Figure 3c is an O_2-σ_t characteristic diagram for these stations. Although oxygen is not a conservative quantity due to a non-zero consumption rate, the distribution of its concentration in the minimum can be used in conjunction with other water mass measurements to confirm features of the flow (Wüst, 1964). The oxygen concentration at the minimum (Fig. 3c) shows that low oxygen water (<3.0 ml l^{-1}) extends along the island arc in a similar manner to the SUW tongue and band of high potential vorticity described above. At 75W it turns northward resembling the π contours of STMW. These similar advective features provide evidence that the northwestward flow persists down to the 800 m depth of the oxygen minimum[5].

The integrated transport above 1000 m (Fig. 3d) has two main features, a large anticyclonic eddy centered at 28°30′N, 75°30′W and (excluding the eddy) a net northwestward transport along the Bahamas Banks. The anticyclonic eddy has a horizontal length scale of about 400 km and extends vertically to a depth greater than 1000 m, as evidenced by significant vertical shear in velocity at that depth. The eddy appears to be elongated to the southeast. Peak velocities of 65-70 cm s^{-1} occur on the western side of the eddy, but the eastern side is less intense (<20 cm s^{-1}). The transport above 1000 m in the eddy is 15-20 Sv.

5. The inferences regarding deeper flow that can be drawn from the distribution of AAIW are limited, because this water mass was rarely detected in the region of the winter survey.

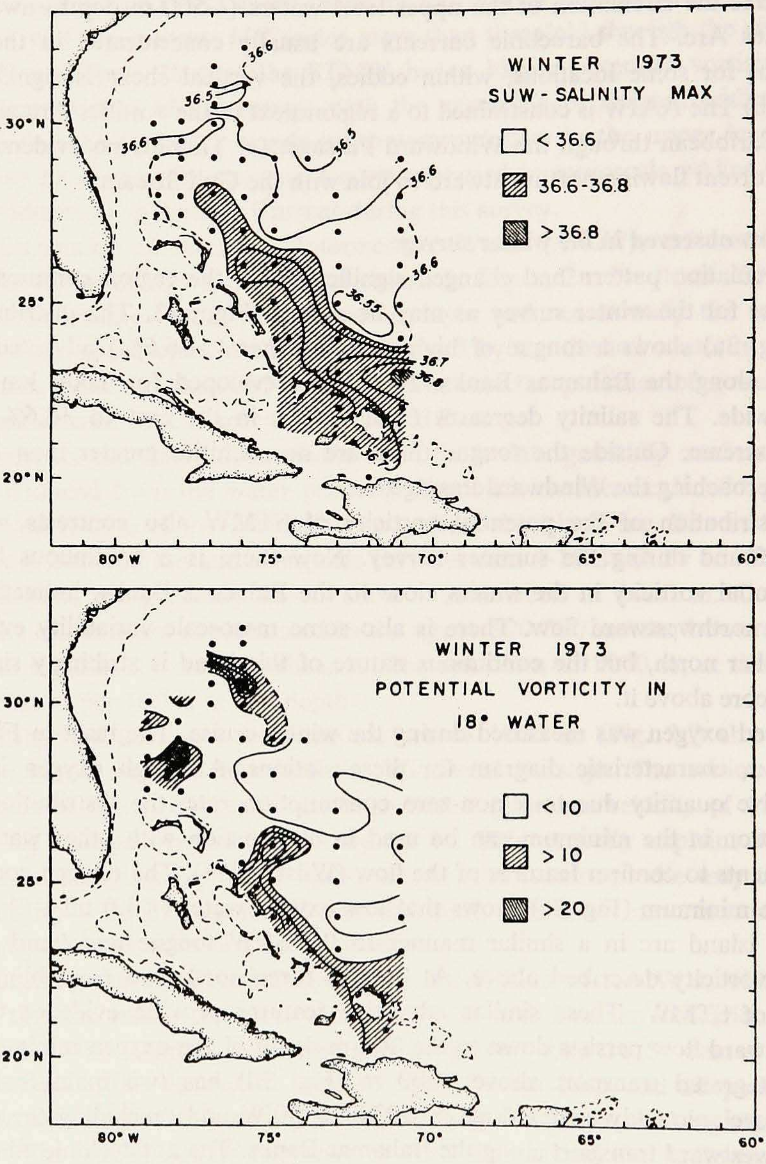
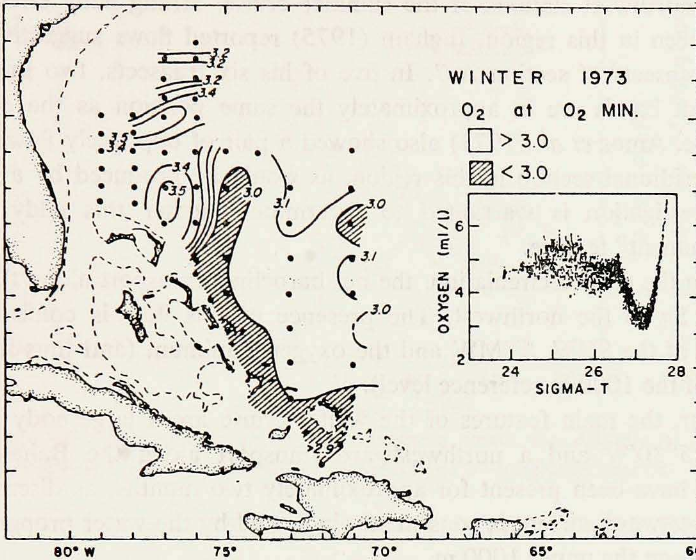
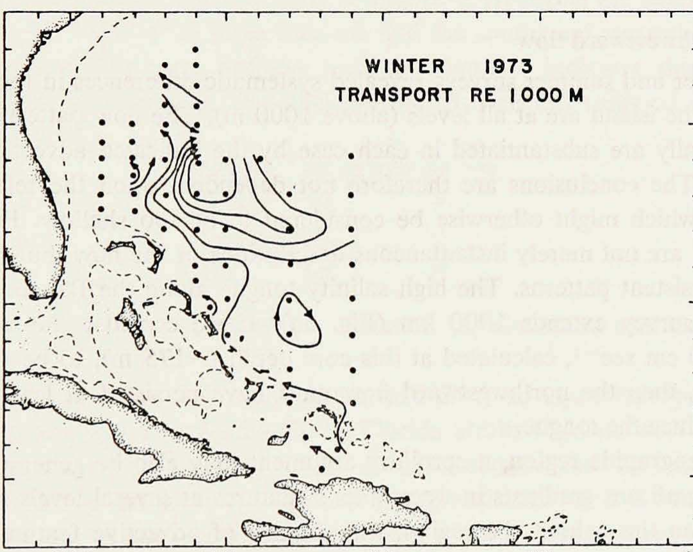


Figure 3. The NMFS winter survey. Dots denote station locations.
(a) Distribution of salinity in the core of the salinity maximum layer indicative of Subtropical Underwater (SUW). Contour interval is 0.05‰.
(b) Potential vorticity (10^{-7} m^{-1} s^{-1}) of water layer with TS characteristics of STMW (18° water).





(c) Distribution of the concentration of oxygen at the oxygen minimum in ml l^{-1}. Contour interval is 0.1 ml l^{-1}. Inset is oxygen-σ_t diagram of all winter stations.

(d) Volume transport referenced to 1000 m. Each line represents a flow of 5 Sverdrups (1 Sv = 10^6 m^3 s^{-1}).

The position of this large eddy is slightly northwest of the anticyclonic circulation in the northwest stations of the summer cruise. Strong eddy circulations are commonly seen in this region. Ingham (1975) reported flows suggestive of eddies in his six transects of section A-7. In five of his six transects, two intense north-south current bands are in approximately the same position as the eddy in this winter cruise. Amos *et al.* (1971) also showed a pair of oppositely flowing currents across a meridional section in this region, as would be produced by a large eddy. Further investigation is warranted to determine whether this eddy may be a "quasi-permanent" feature.

Excluding the eddy recirculation, the net baroclinic transport along the Bahamas Banks is 9 Sv to the northwest. The presence of this flow is confirmed by the distribution of the SUW, STMW and the oxygen minimum (and thus it is not just an artifact of the 1000 m reference level).

Altogether, the main features of the winter cruise are a large eddy centered at 28°30′N, 75°30′W and a northwestward transport along the Bahamas Banks, which must have been present for approximately two months, as discussed below. This northwestward current is consistently indicated by the water property distributions throughout the upper 1000 m.

7. The northwestward flow

The winter and summer surveys revealed systematic differences in the large-scale flow along the island arc at all levels (above 1000 m). The flow patterns calculated geostrophically are substantiated in each case by the indicated advection of water properties. The conclusions are therefore not dependent upon the reference level (1000 m), which might otherwise be considered to be too shallow. Furthermore, the patterns are not merely instantaneous descriptions of the flow, but must in fact indicate persistent patterns. The high salinity tongue along the Bahamas Banks in the winter survey extends 1000 km (Fig. 3a). If we consider the velocities, of order 10-20 cm sec^{-1}, calculated at this core depth ($\sim$175 m), to be indicative of the average, then the northwestward flow must have persisted at least 50 to 100 days to produce the tongue.

In this geographic region, a corollary argument may also be generated: because there are significant gradients in watermass signatures at several levels in the upper water column throughout the region, the absence of advective features along the island arc indicates that no organized Antilles Current had immediately preceded the summer survey, although many factors could influence an estimate of the persistence of its absence.

To address the question whether the observed temporal difference may represent a seasonal variation[6], we examined the quarterly average values of wind stress curl

6. A review of historical hydrographic data from NODC was inconclusive regarding the possible seasonal presence of a SUW salinity maximum along the Bahamas, which would result from a northwestward current. Stations available were scattered very unevenly through the year, so no statistically significant trend could be determined.

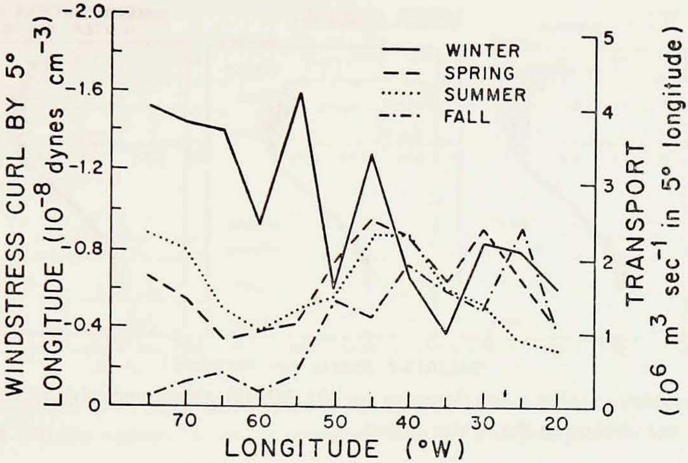


Figure 4. Quarterly values of the curl of the windstress across the Atlantic at 25 N latitude, and the corresponding southward Sverdrup transport per 5° longitude interval.

across the ocean at 25N latitude, reported in Hellerman (1967). These data are plotted relative to the left ordinate scale of Figure 4. Applying the Sverdrup (1947) relation ($V = \beta^{-1}$ curl τ) to these data we find the southward vertically integrated volume transport. The right ordinate scale in Figure 4 indicates this southward transport per 5° of longitude. The total southward transport summed across 25 N latitude is:

Winter	32	(x 10^6 m^3 $^{-1}$)
Spring	20	"
Summer	19	"
Fall	12	"

It is curious to note that most of the variation in windstress curl occurs in the western basin.

To counterbalance the basin-wide southward flow, an equal transport of water is assumed to flow northward through the Florida Straits together with any western boundary current which may exist east of the Bahamas. In the winter survey, when the Sverdrup transport is high, a northwestward current was observed, whereas none was present in the summer survey when the Sverdrup transport is low.

This correspondence may be coincidental. In the Florida Straits, Niiler and Richardson (1973) found short-term variations in transport to be comparable to the seasonal changes. On the basis of ninety transects of the Florida Current they resolved a seasonal cycle with a maximum in June and minimum in December (33.6 and 25.4 $\times$ 10^6 m^3 s^{-1} respectively). The cycle is nearly opposite in phase to the cycle of Sverdrup transport noted above. This curious phase difference remains unexplained.

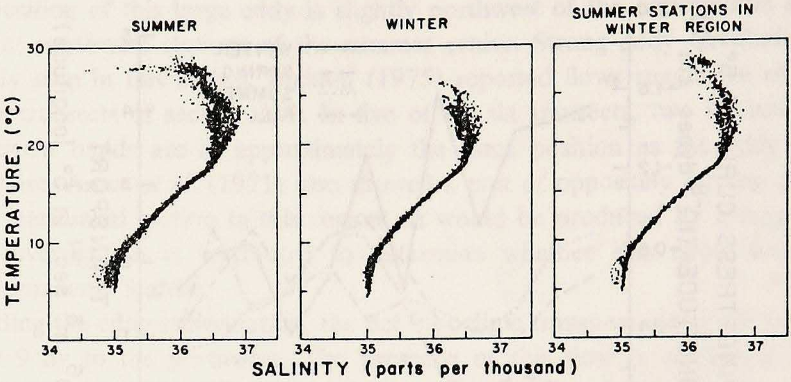


Figure 5. Temperature-salinity relationships for the NMFS a) summer, b) winter survey data and c) summer stations in the winter region.

At this point, we can draw an important negative conclusion regarding the Antilles Current. It does not continually exist. Instead, the flow field and water properties demonstrate the presence of numerous eddies in the region, both in the summer and the winter. Altogether it is plausible but not certain that the Antilles Current may be seasonally (as opposed to sporadically) present.

8. Flow through the Windward Passage

The summer and winter surveys evidenced distinct differences in the total volume transport approaching the Windward Passage and in the strength of the AAIW core from the stations in the region common to the two surveys. Figure 5 presents the TS relationships from the summer and winter surveys separately, on the left, and from the set of summer stations which were taken within the winter survey region, on the right. In the area common to both surveys, only some of the summer stations had a distinct AAIW core. None of the winter stations had such a strong salinity minimum. This suggested a simple signature to seek in examining historical data from NODC in other years to see if a seasonal pattern is present.

We inspected all the deep (⩾ 2000 m) hydrostation data in the NODC files for three regions which are indicated by dotted perimeters on Figure 1, located in the Windward Passage and on the Atlantic and Caribbean side thereof. In each area there were sufficient stations to represent fall (September-November), winter (December-February) and spring (March-May) but too few in the summer. We carefully examined the TS relationship for each station and threw out all that did not satisfy the following criteria, which we felt were indicative of the quality and care with which the data had been gathered and reported: a station could have no TS points deviating significantly from the median curve in water colder than 4°C (± 0.015‰) or in the range 12°-18°C (± 0.05‰). (The median curve agrees well with Wright and Worthington (1970) in these ranges.) Generally, it was not

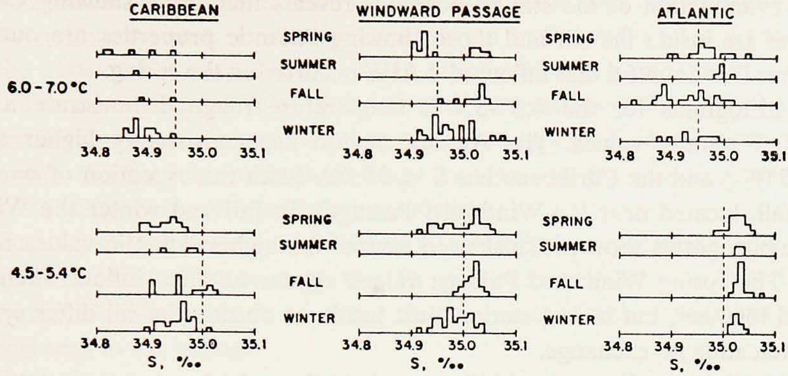


Figure 6. Histograms of salinity distribution in .01‰ class intervals for Caribbean, Windward Passage and Atlantic regions for two temperature intervals and grouped by season.

difficult to determine which stations to keep or reject. Of 235 available stations, we have kept 124 in 18 separate years from 1922 to 1974.

As can be noted in Figure 5, the core of AAIW influence is predominantly in the (*in situ*) temperature range 5.5 to 7.5°C. At greater depths in this region Mediterranean Water increases salinities principally in the temperature range 4° to 5.5°C. There is a distinct difference between the shape of the TS curves in the Atlantic and Caribbean region. The "ATL" region has considerable variability in the AAIW core (S ≅ 34.95 ± 0.13‰, but a small range of higher salinities in the core affected by Mediterranean Water (S ≅ 35.03 ± .04‰). By contrast these higher salinities are prevented from entering the Caribbean (in any substantial quantity) by the sill depths of the entrance passages, of which the Windward Passage is the deepest. Thus the Caribbean ("CAR") TS curves have a salinity minimum which spans a broader temperature range, with lower salinities and more restricted variability than in the "ATL" area.

Figure 6 is a collection of histograms of the occurrence of a given salinity by 0.01‰ classes for two temperature ranges, 6°-7°C (AAIW) and 4.5-5.4°C[7]. The 6°-7°C Atlantic data show a considerable range of salinities by season and within seasons. There is a slight tendency for higher salinities in the spring and summer and lower in the fall and winter. By contrast for the 6°-7°C temperature range the Caribbean salinities never exceed 34.95‰, although only winter and spring are well represented. The Windward Passage histograms show salinities higher than 34.95‰ in the fall and winter, indicative of inflow from the Atlantic. Those 37 "WP" stations are drawn from four different years and do not have salinities as low as are typical in the "CAR" region. During the spring a bimodal distribution of "WP" salinities indicates the presence of both "ATL" and "CAR" waters, but

7. The NODC data are bottle samples, so the temperature ranges were chosen to be broad enough that any given station would usually have a bottle representing each range.

careful examination of the station positions reveals that those showing Caribbean influence are inside the sill and those showing Atlantic properties are outside the sill[8]. Thus it is doubtful that inflow of AAIW occurred in the spring.

The histograms for the 4.5°-5.4°C temperature range demonstrate a similar pattern of salinity values. The Atlantic region has consistently higher salinities ($S > 35.0‰$) and the Caribbean has $S < 35.0‰$ (with the exception of one station in the fall, located near the Windward Passage). In fall and winter the Windward Passage histograms show peaks skewed toward the higher Atlantic values requiring inflow. The spring Windward Passage values appear to show inflow when all are grouped together, but in fact stations just inside or outside the sill differ systematically, indicating no exchange.

The possibility of a seasonal flow pattern through the passages entering the Caribbean has been raised previously (Sukhovey and Metal'nikov, 1968). During the winter they find a flow into the Caribbean Sea in the surface waters (<600-800 m) and a flow out in deeper waters (>1000 m) in both the Windward and the Anegada-Jungfern Passages. Their data were taken in the winter and consisted of 25 hours of current meter records and some hydrostations. They attribute the existence of this two level system to the forcing of the Trade Winds, which hypothetically drive the surface waters into the Caribbean and set up a baroclinic return flow. This supposition is tenuous considering the short time period of their observations, but it illustrates the complexity of the situation.

It is attractive to postulate a seasonal regularity to the variability seen in the flow through the Windward Passage. The above histograms of NODC data do show a consistent pattern of AAIW flowing into the Windward Passage in the four years representing winter and fall, and an absence of such flow in seven of the eight years representing spring. It is improbable that this is a random pattern, however we do not feel that the data justify a firm conclusion regarding an annual cycle, because of several cautions which should be considered. Summer is insufficiently represented in any of the regions. In other seasons the data for some regions are heavily weighted by one year. (For example in the ATL-fall set all but two of the good stations were from 1961.) Furthermore, in no year were all three regions represented, therefore comparisons between regions do not take into account year-to-year variations.

In summary, subject to these cautions, the pattern found in these NODC data consistently indicates flow of AAIW from the Atlantic into the Windward Passage during fall and winter and the lack of exchange in spring.

9. Summary and conclusions

Two surveys, summer and winter, show the currents east of the Bahamas and north of the Antilles Archipelago to be quite variable and dominated by mesoscale

8. Eight different years are represented in the WP-spring histogram, and with the exception of a 1933 station, all those with $S < 34.95‰$ are inside the sill.

eddy motion. The northwestward surface flow associated with the Antilles Current does not continually exist. Instead, we observe a well developed northwestward flow in the upper 1000 meters in the winter, which was not present in the previous summer. The occurrence of this northwestward current coincides with the yearly maximum in the gyre-wide southward Sverdrup transport. Both of these are out of phase with the fluctuations in the volume transport of the Florida Current, the maximum of which occurs five months later in June.

The flow of deeper waters (AAIW) into the Windward Passage also varies, based upon seasonal differences in the TS relationships found in NODC data. Inflow to the Caribbean tends to occur during the fall and winter, and no exchange was seen in the spring.

The above findings may be suggestively associated as a guide for planning future work, but the relationships are admittedly speculative given the present data: In the summer/fall when the Sverdrup transport has decreased to its minimum, there is no Antilles Current along the Bahamas, but the flow through the Windward Passage and thence through the Florida Straits is greatest. In the winter/spring when the Sverdrup transport has increased to its maximum, an Antilles Current spins up, the flow through the Windward Passage is inhibited, and the transport within the Florida Straits goes to a minimum.

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