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On the sources of the Florida Current

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Abstract—In our opinion roughly 13 Sv or 45% of the transport of the Florida Current is of South Atlantic origin, as compensation for the cross-equatorial flow of North Atlantic Deep Water. Of the 8.9 Sv moving through the Straits of Florida with temperatures above 24°C in the upper 100 m of the water column, 7.1 Sv is composed of comparatively fresh water coming through the southern Caribbean passages from the tropical South Atlantic. Saltier surface water, 1.8 Sv, enters from the North Atlantic through Windward Passage, as does most of the 18° Water in the Florida Current. A South Atlantic contribution for the uppermost layer is clear-cut because the surface water in the open Atlantic north of the Caribbean is comparatively cold and salty and intrudes south as Subtropical Underwater or Salinity-Maximum Water below a comparatively warm and fresh layer 50–100 m thick, which could hardly be transported from the North Atlantic. Of the 13.8 Sv transported through the Caribbean in the 12–24°C temperature range, 13.0 Sv is of North Atlantic origin, with about 0.8 Sv of comparatively fresh South Atlantic water on the western side of the Florida Straits having entered the Caribbean on the southern side of St. Vincent and St. Lucia Passages. Of the 6 Sv transported by the Florida Current in the 7–12°C temperature range, 5 Sv appears to originate in the South Atlantic. Our estimate of the 13 Sv of South Atlantic and 16 Sv of North Atlantic origin for the total transport of 29 Sv for the Florida Current, along with partitioning in the aforementioned temperature ranges, is approximately consistent with open ocean sections along 24°N and with several previous investigations.

We have formed a new estimate of the transport into five key Caribbean passages, yielding 28.8 Sv for the temperature range appropriate to the Straits of Florida off Miami, in close agreement with independent transport measurements for the Florida Current. The five passages and their contributions are: Grenada (7.7 Sv), St. Vincent (7.9 Sv), St. Lucia (3.8 Sv), Dominica (2.6 Sv), and Windward (6.8 Sv). Breakdowns of these passage transport estimates into broad classes by temperature range agree to within about 2 Sv in comparison with similar quantities for the Florida Current. Anegada Passage may transport 0.5 Sv of water that exits through the upper 200 m or so of the Florida Current, and the mid-depth (5–12°C) flow in this passage and in the general vicinity of the Caribbean deserves further examination.

1. INTRODUCTION

STOMMEL's (1957) picture of the thermohaline circulation in the Atlantic Ocean had about 20 Sv (1 Sv = 10^6 m^3 s^{-1}) of abyssal flow crossing the equator and entering the South Atlantic, with a corresponding cross-equatorial return transport to the North Atlantic in the upper ocean. This guess (STOMMEL, personal communication), partially motivated by the strong southward-flowing abyssal currents along the western boundary of the Atlantic suggested by WÜST (1957), slipped from prominence until recently. Then HALL and

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Bryden (1982, hereafter HB 82) found a large southward transport of abyssal water across an open ocean section along 24°N, 19 Sv of water less than 7°C. Others (i.e. Gordon and Piola, 1983; Gordon, 1986) also rekindled interest in a possible large interbasin exchange. Perhaps it should be noted in this regard that Wüst (1957) had 15 Sv in the 0–1200 m depth range moving north in the eastern South Atlantic as partial compensation for the southward transport of North Atlantic Deep Water (NADW).

The southward transport of 12.4 Sv in the upper ocean across 24°N found by HB 82, all for temperatures warmer than 12°C, is less than half of the mean transport in the Florida Current (29–32 Sv; Schmitz and Richardson, 1968; HB 82 used a total of 29.5 Sv). Of the 12.4 Sv found by HB 82 to be flowing south across 24°N, 11.4 Sv were located at 12–24°C, in reasonable agreement with the 13.0 Sv transport of North Atlantic water we find moving in through the Caribbean passages in this temperature range, to a large extent Subtropical Underwater (Wüst, 1964) and 18° Water (Worthington, 1959). The source(s) of the well-established Florida Current transport have not yet been clearly sorted out, with Worthington (1976) postulating a North Atlantic origin for more or less the entire 30 Sv.

Although there is general agreement on substantial transport north across the equator, much of the upper ocean flow along and close to the North Brazil Coast is thought to retroflect or recirculate (Metcalf, 1968), a major problem in rationalizing a sizeable net transport of warm water from the South Atlantic into the Caribbean. Worthington (1976) summarizes the objections to a "large" net exchange between the North Atlantic and the South Atlantic, especially in the west; he postulates an exchange of 5–6 Sv confined to the far eastern side of the Atlantic Basin. An essential hydrographic result is illustrated in Fig. 1 (a smoothed adaptation of Fig. 4 in Metcalf, 1968), which shows the existence of a temperature–oxygen (T–O_2) front at mid-depths in the temperature range 12–24°C between waters of North vs South Atlantic origin in the region just off the coast of northern Brazil. The sum of the pioneering by Metcalf and Stalcup in the tropical Atlantic

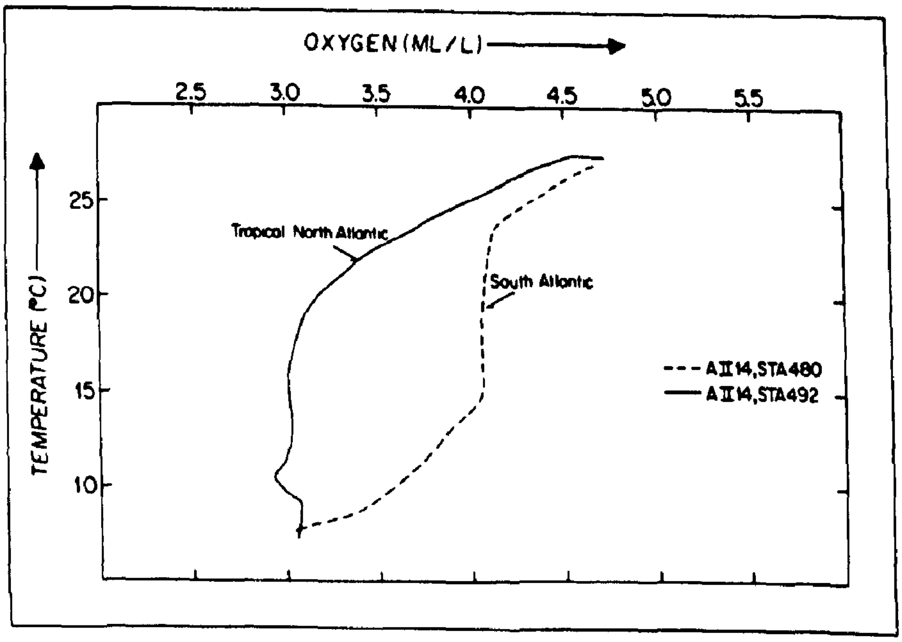


Fig. 1. Schematic temperature (T) vs oxygen (O_2) curves for the western tropical Atlantic off the northern coast of Brazil.

demonstrated that most of the warm water in the 12–24°C temperature range flowing into the North Atlantic along the coast of South America returns toward the South Atlantic, primarily forming the Equatorial Undercurrent (METCALF and STALCUP, 1967) and is the origin of the contemporary picture of retroflection and "separate" North Brazil Coastal Current and Guiana Current Systems (BOYD, 1986; FLAGG *et al.*, 1986). As a major point in the following, we emphasize that the restriction in Fig. 1 does not apply either to the ventilated near-surface waters in the upper 50–100 m of the tropical Atlantic, where temperatures are greater than 24°C, or for temperatures less than 12°C.

STALCUP and METCALF (1972, hereafter SM 72) made direct current as well as hydrographic measurements in several of the Caribbean passages, leading to estimates of transport partitioned by water properties. They emphasized that the water moving into the Caribbean at mid-depths where temperatures are 12–24°C is primarily of North Atlantic origin. A detailed comparison of their results with Florida Current data has not yet been attempted; such analysis and interpretation of the SM 72 data is a major component of the present work. We agree that most of the water flowing into the Caribbean (13.0 out of 13.8 Sv) and out through the Florida Current in the 12–24°C temperature range is of North Atlantic origin, but find a South Atlantic origin or residence for most of the flow with temperatures higher than 24°C or lower than 12°C. METCALF *et al.* (1974, 1977) also made hydrographic and current measurements in Windward Passage, where a recent inverse analysis (ROEMMICH, 1981) plays a central role in our results. The currents in Anegada Passage (METCALF, 1976) need further observational attention.

A variety of data will be used in the following to examine approximately how much of what type of water may contribute to the transport of the Florida Current. As a new ingredient in the investigation of interbasin exchange, we choose the Straits of Florida and the Caribbean passages as a much simpler area than the western tropical Atlantic to study possible South Atlantic origin. In Section 2, the general characteristics of the Florida Current are outlined. The partitioning of transport with temperature for a variety of locations is summarized in Section 3. In Sections 4–7 the possible sources of the Florida Current are discussed, for each of three (four) temperature ranges, emphasizing the flow found by SM 72 and ROEMMICH (1981) through the Caribbean passages, including a special treatment of Dominica Passage. Finally, exchange with the South Atlantic along with implications for the larger-scale North Atlantic circulation are described in Section 8.

2. THE FLORIDA CURRENT

Although many investigations of the western tropical Atlantic have shed light on the circulation there and on the exchange between the South and North Atlantic, it is an extremely complicated area (PARR, 1937a; COCHRANE, 1963, 1969; METCALF and STALCUP, 1967; METCALF, 1968; NEUMANN, 1969; GIBBS, 1970; SM 72; FROELICH *et al.*, 1978; COCHRANE *et al.*, 1979; FLAGG *et al.*, 1986; RICHARDSON and REVERDIN, 1987; SCHMITT *et al.*, 1987; MULLER-KARGER *et al.*, 1988). The relationship of the flow in the tropical Atlantic to the transport of the Florida Current (F.C.), and consequently the North Atlantic Subtropical Gyre, is still an open question. To the extent that the southward flow of NADW is balanced by comparatively shallow flow through the Straits of Florida, we can approach interbasin exchange by focusing on the properties of the flow in the F.C. Recent observations by ROEMMICH and WUNSCH (1985) and LEAMAN *et al.* (1989) are important new data bases in this regard. A first basic premise of the present work is that the simplicity as well as the comparatively well-established characteristics of the F.C. within the Straits of Florida leads initially to an easier focal point for examining much of the interbasin exchange relative to the extremely complicated western tropical Atlantic. GORDON (1986, his Fig. 2a) does suggest that the (net) upper ocean compensation for NADW moves through the Straits of Florida. We find that most (~13 Sv) of the warm water associated with the interbasin exchange does move through the F.C. with perhaps a few Sv (HB 82) involved in the open Atlantic east of the Bahamas.

The F.C. has one of the, if not the, best-established mean transports of any current in the world's oceans, in large part due to the well-defined boundaries of the current due to the restrictive geometry of the Straits of Florida, and also to the relatively low amplitude and benevolent frequency spectra of the fluctuations. The total tranport estimate of 32 ± 3 Sv by SCHMITZ and RICHARDSON (1968), as well as the general aspects of their estimates of temporal variability, have held up under intense scrutiny and new data acquisition for 20 years (e.g. LEAMAN *et al.*, 1987; who report 31.7 ± 3 Sv). Directly observed transport has recently been partitioned with temperature by LEAMAN *et al.* (1989).

ROEMMICH and WUNSCH (1985) recently acquired high quality and complete hydrographic data in the F.C. and temperature, salinity and oxygen sections are shown in Fig. 2, with T–S and T–O_2 curves in Figs 3 and 4. The T–S curves in Fig. 3 are like those previously described by PARR (1935, 1937b) and WENNEKENS (1959). The existence of a core of Salinity-Maximum Water on the right-hand side of the Straits looking downstream is a ubiquitous feature of all sections across the F.C. and similarly for most Caribbean passages. The curves in Figs 3 and 4 include cross-stream summaries for selected groups of the 11 stations (numbered 240–250 from east to west, *Atlantis II* cruise 109) occupied across the Straits by ROEMMICH and WUNSCH (1985), representing generic T–S and T–O_2 curves for two and three cross-stream regions, respectively. Figure 3 also contains examples of how individual stations may deviate from the summary T–S curves. 18° Water (temperature = 17.9 ± 0.3°C, salinity = 36.5 ± 0.1; according to WORTHINGTON, 1959) is represented by a solid bar in Fig. 3 and the corresponding O_2 maximum near 18°C is apparent for the T–O_2 curve representing "F.C. East" in Fig. 4a. On the sections (Fig. 2), 18° Water resides just under the core of Salinity-Maximum Water on the eastern side of the Straits of Florida.

The three F.C. T–O_2 curves (hereafter F.C. West, F.C. Middle, F.C. East) in Fig. 4a do not resemble closely either of the two tropical Atlantic curves transposed from Fig. 1 onto Fig. 4a. The F.C. T–O_2 curves in the 12–24°C range are generally inbetween the two SM 72 curves in Fig. 1, except for the existence of O_2 maxima (larger even than typical South Atlantic values) for F.C. East near 18°N Water and for F.C. West between 20 and 25°C, both maxima suggesting ventilation or "recent" contact with the atmosphere. The T–S curves for the stations in Fig. 1 are generally fresher (Fig. 4b) than the least saline F.C. curve (West) except that the "northern station" from the tropical Atlantic is much closer in the 15–25°C range. The saltier curve is labeled F.C. Middle and East, in partial correspondence with the stations allocated to similar regions in the T–O_2 curves. Our conclusion from these figures is that the South Atlantic contribution to the transport of the F.C. is not obviously dominated by direct flow from the North Brazil Coastal Current.

Prior to partitioning Caribbean passage transports with temperature for comparison with similar F.C. estimates, we want to see how the passage T–S and T–O_2 curves relate to those for the F.C. Many of the T–S curves for stations in the Caribbean passages (Fig. 4c indicates the geography of the southern inlets) resemble portions of the curve labeled F.C.

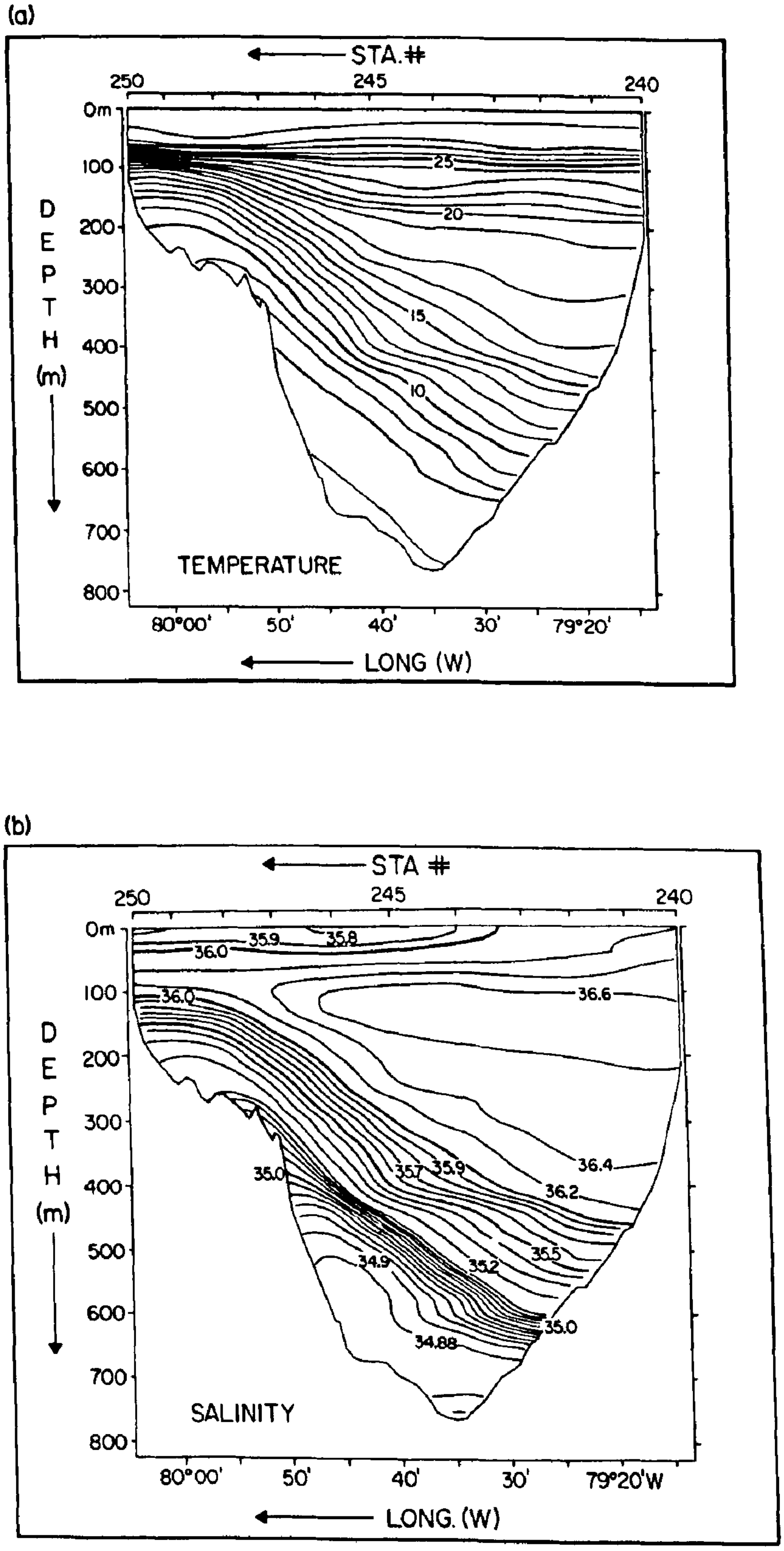


Fig. 2. Florida Current sections, based on results from ROEMMICH and WUNSCH (1985): (a) temperature contours, (b) salinity contours, (c) oxygen contours.

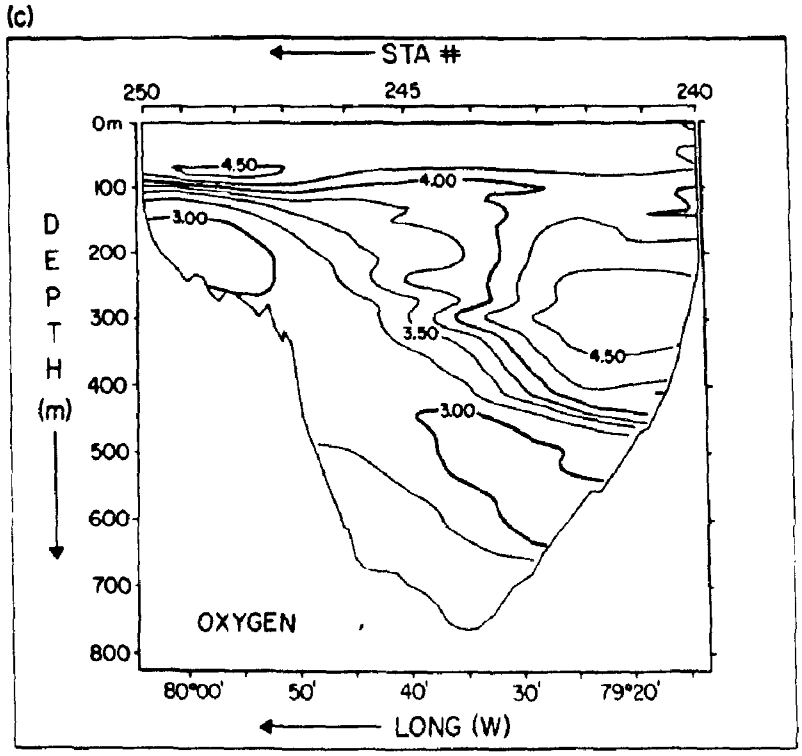


Fig. 2. (cont.)

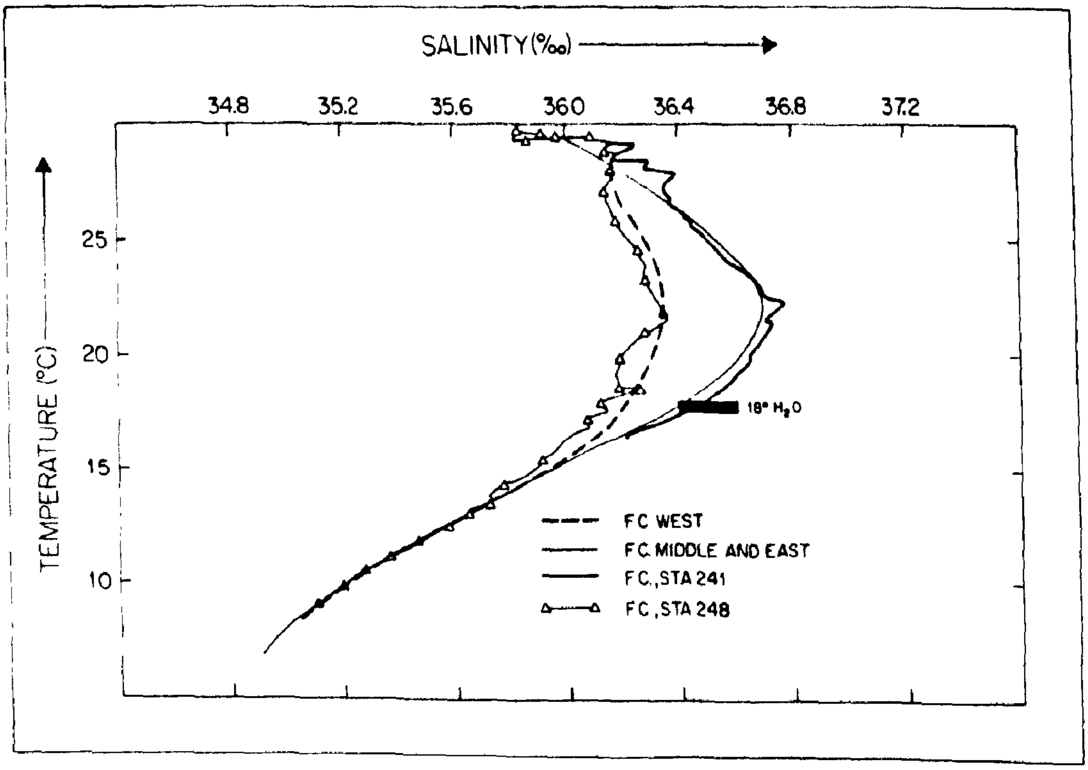


Fig. 3. Generic T–S curves for the Straits of Florida, in comparison with specific stations. 18° Water according to Worthington (1959) is indicated by a solid bar on the T–S plot. See text for an explanation of the origin of the different curves.

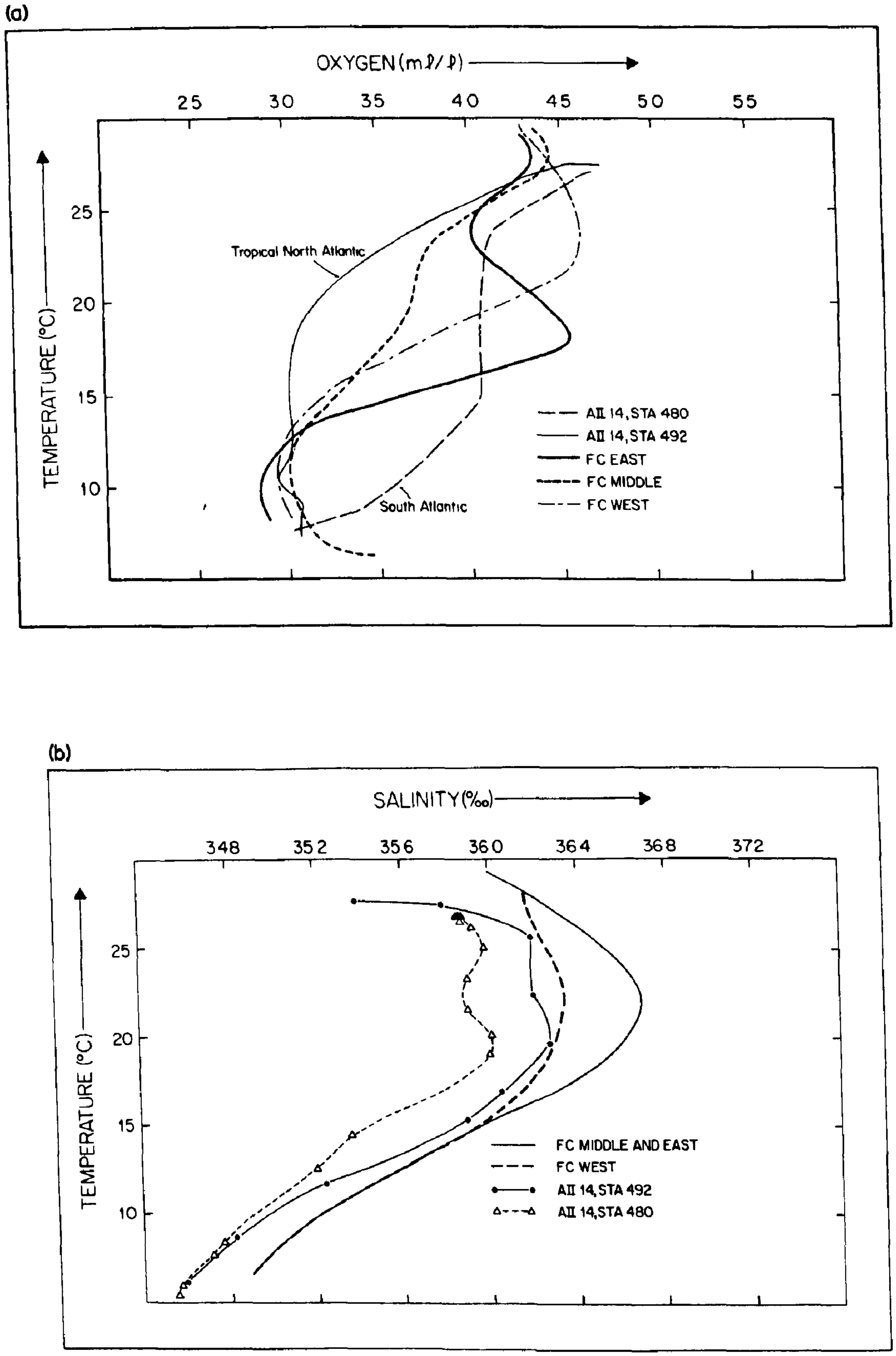


Fig. 4. (a) T–O_2 and (b) T–S curves for the Florida Current in comparison with the North Brazil Coastal Current plots in Fig. 1. (c) Caribbean passage locations.

Middle and East in Fig. 3. Two of the few Caribbean inlet stations (Metcalf and Stalcup, 1967; Metcalf *et al.*, 1971, 1973, 1974, 1977) that we have found to contain the fresh portions of the F.C. West T–S curve for the temperature range 15–25°C in Fig. 3 are located on the southern side of St. Vincent Passage (Fig. 5a). In Fig. 5a and b, the hydrographic stations are numbered 1702–1706 (Metcalf *et al.*, 1971) from north to south across St. Vincent Passage. Corresponding T–O_2 curves (Fig. 5b) do not overlay F.C. West nearly as well as the T–S curves. The analogous southernmost two stations from St. Lucia Passage (Fig. 5c) show vestiges of T–S character like F.C. West, and like St. Vincent (Fig. 5a) the T–S curves from the northern stations (numbered in Fig. 5c and d from 1693

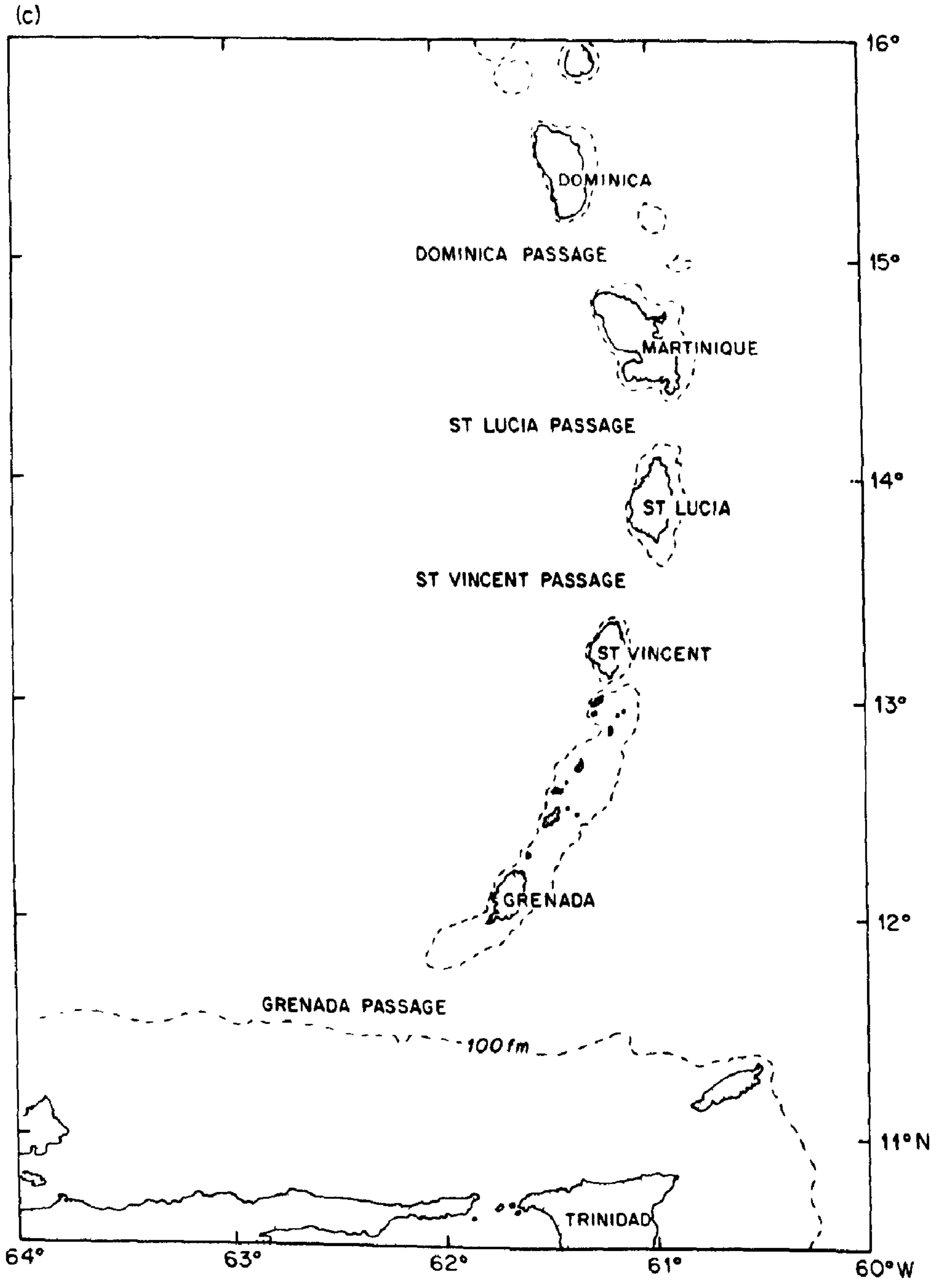


Fig. 4. (cont.)

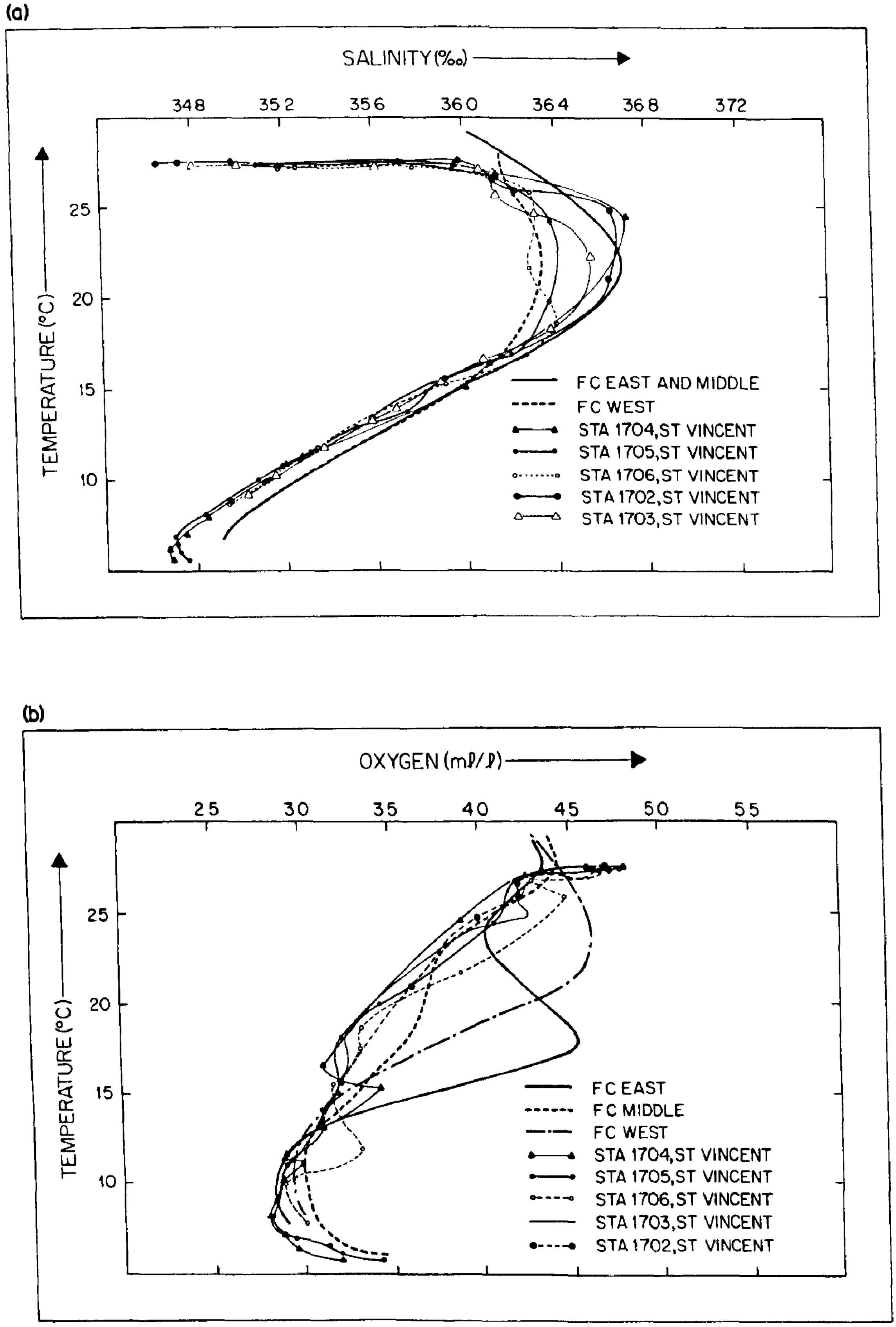
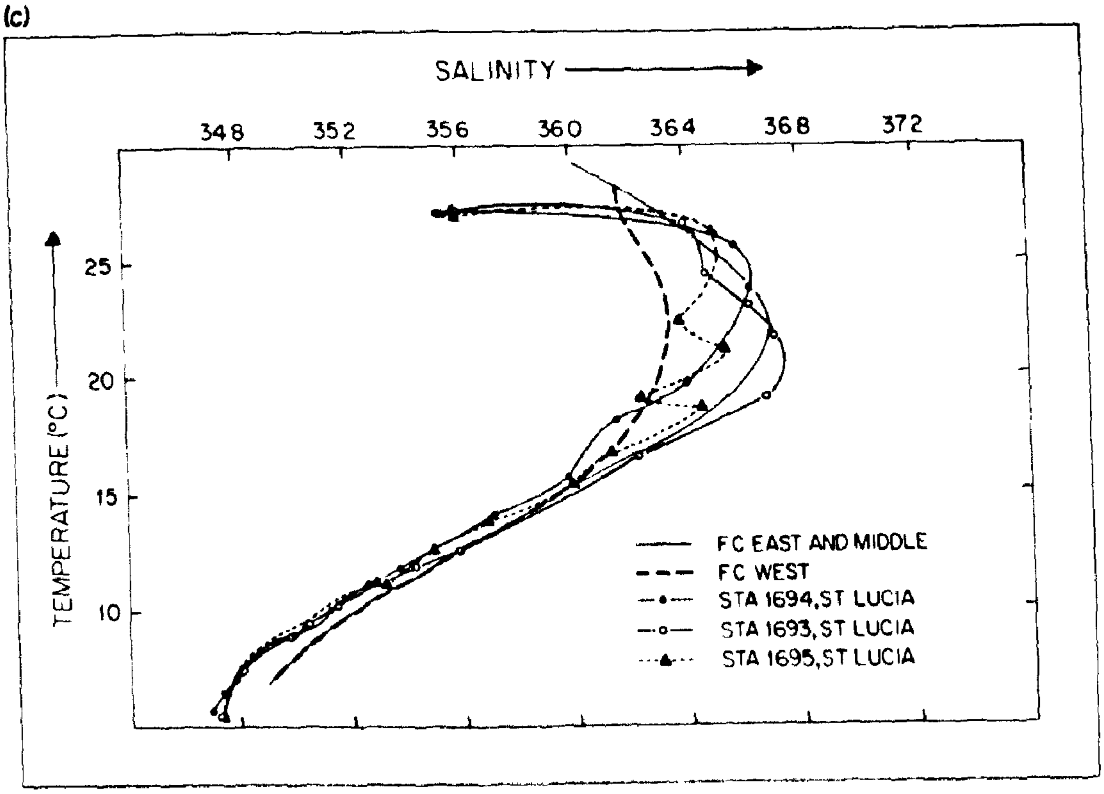


Fig. 5. (a) T–S curves for St. Vincent Passage in comparison with the Florida Current, and (b) T–O_2 curves for St. Vincent. (c,d) Similarly for St. Lucia Passage.

(c)


SALINITY
348
352
356
360
364
368
372
TEMPERATURE (°C)
25
20
15
10
FC EAST AND MIDDLE
FC WEST
STA 1694, ST LUCIA
STA 1693, ST LUCIA
STA 1695, ST LUCIA

(d)

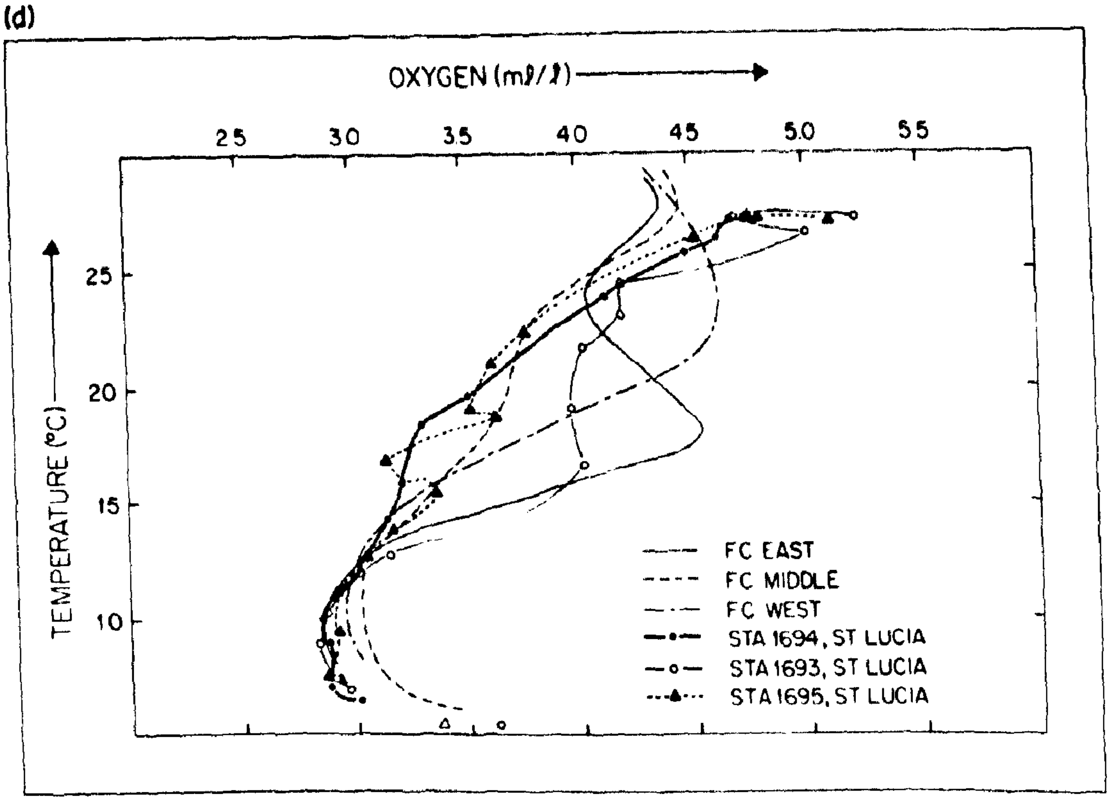

OXYGEN (ml/l)
2.5
3.0
3.5
4.0
4.5
5.0
5.5
TEMPERATURE (°C)
25
20
15
10
FC EAST
FC MIDDLE
FC WEST
STA 1694, ST LUCIA
STA 1693, ST LUCIA
STA 1695, ST LUCIA

Fig. 5. (cont.)

to 1695, north to south, after SM 72) resemble F.C. Middle and East. T–O_2 curves, however (Fig. 5d), mostly resemble F.C. Middle, as is the case in St. Vincent Passage (Fig. 5b).

Inflow at mid-depth appears to occur only on the northern side of Grenada Passage (see below) and the T–S curves there (Fig. 6a) are salty, mostly like F.C. Middle and East, as is the case in both Dominica (Fig. 6b) and Windward Passages (Fig. 6c). In Fig. 6a, the T–S curves for Grenada Passage based on Stas 1662 and 1675 are occupations at the same location in the core of the current, taken approximately 4 days apart. The T–O_2 curves for Grenada (Fig. 6d) and Dominica Passages (Fig. 6e) follow F.C. Middle (Fig. 3) like those for St. Vincent and St. Lucia. In Windward Passage (Fig. 6f), where all the data are from *Knorr* cruise 37 (KN 37), the T–O_2 curves show the maximum associated with 18° Water. In the 7–12°C range the southern passages are fresh and Windward slightly salty relative to the F.C., spanning the T–S staircase range found by SCHMITT *et al.* (1987) outside the Caribbean. The T–S curves across Yucatan Channel appear more nearly alike in the 7–12°C range than those across the Caribbean passages (PARR, 1935, his Fig. 22; see also WORTHINGTON, 1976, Fig. 23, p. 60). In the southern passages for the 7–12°C range, O_2 values are like F.C. West and F.C. East and low relative to F.C. Middle, i.e. in the colder part of this region. Deep (7–12°C) Windward Passage oxygens (Fig. 6f) are notably displaced toward high O_2 from the F.C. curves. The hydrography and some aspects of the current structure in the Anegada–Jungfern Passage have been examined by METCALF *et al.* (1973), STALCUP *et al.* (1975) and METCALF (1976). Deep salinities are intermediate between those from Dominica and Windward Passages, as are T–O_2 values, except near 18° Water, as discussed in Section 8. According to SM 72, there is flow in through the southern Caribbean passages with temperatures just lower and salinities fresher than any observed to flow through the Straits of Florida off Miami, a point amply illustrated by WORTHINGTON (1976, Fig. 23).

3. TRANSPORT–TEMPERATURE PARTITIONING

HB 82 balanced a calculation of transport across 24°N between the Bahamas and Africa with that in the Straits of Florida and partitioned their results with temperature approximately as contained in Table 1. HB 82 chose the temperature ranges as indicated in Table 1 to coincide with WORTHINGTON (1976) and scaled their results by a 29.5 Sv direct transport estimate for the F.C. In Table 1 we have used a slightly different interpolation scheme from HB 82. ROEMMICH (1981) made similar estimates with other inverse techniques for the Caribbean Sea. LEAMAN *et al.* (1989) have recently partitioned transport with temperature for the F.C. based on direct measurements. In Table 2, some of these breakdowns are expanded in temperature range and new calculations of similar quantities for selected Caribbean passages (see below) are appended. In Tables 1 and 2 (where + is northwards and − southwards), transport allocations have been listed for temperature ranges that are to some extent summaries of these authors' results, which may be referred to for more detail.

For the F.C., the comparison between results from LEAMAN *et al.* (1989) and HB 82 in Tables 1 and 2 is within ±1 Sv, and the partitioning for the Caribbean by ROEMMICH (1981) in Table 1 is similarly close to both. Please note, however, that the total transport by LEAMAN *et al.* (1989) in Table 1 is 29.9 Sv roughly 2 Sv less than the value of 31.7 ± 3.0 Sv reported for the same data set by LEAMAN *et al.* (1987), well within their standard deviation

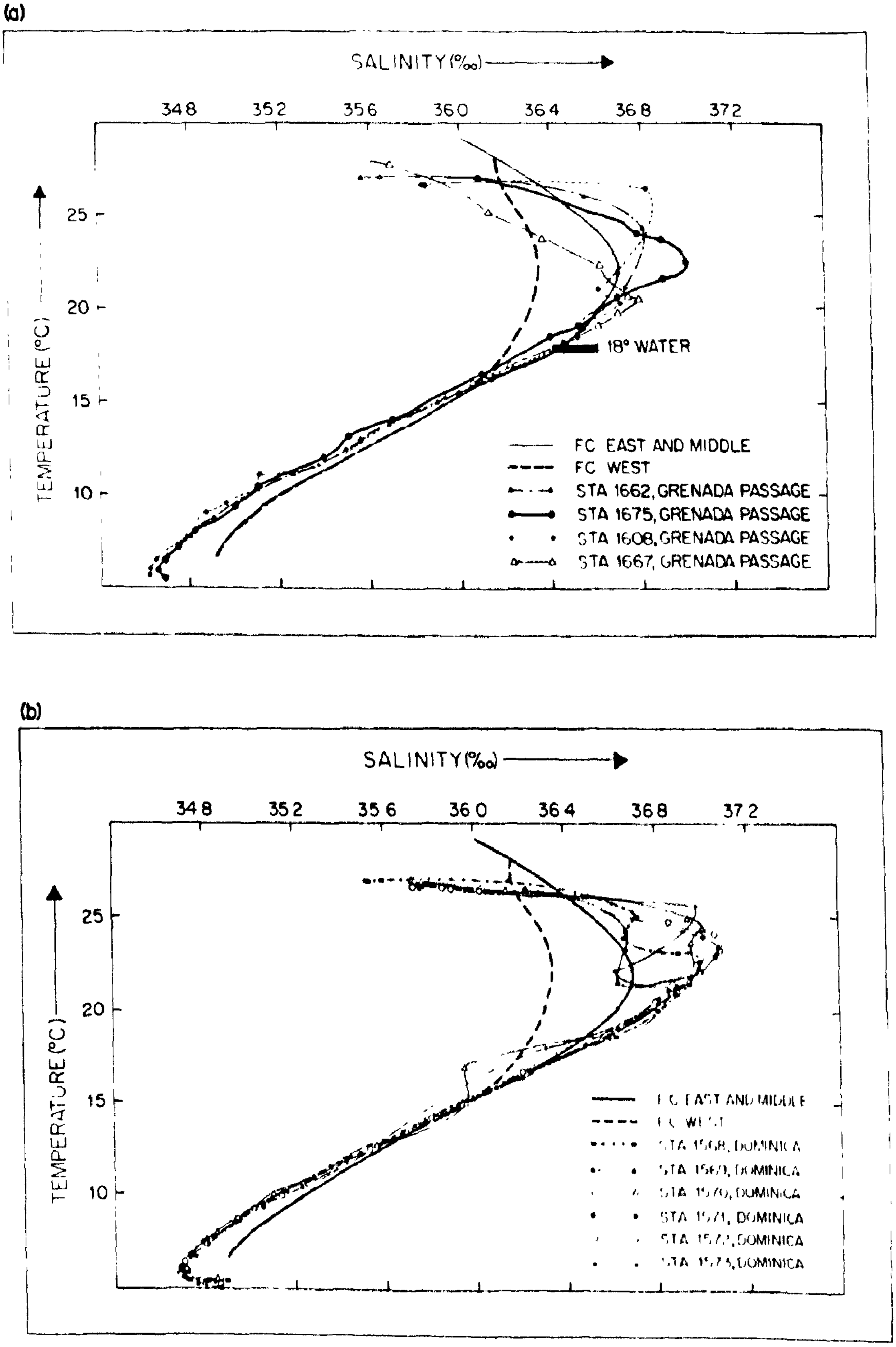


Fig. 6. T–S and T–O_2 curves for a variety of Caribbean passages in comparison with the Florida Current: (a) T–S curves, Grenada, (b) T–S curves, Dominica, (c) T–S curves, Windward, (d) T–O_2 curves, Grenada, (e) T–O_2 curves, Dominica, and (f) T–O_2 curves, Windward.

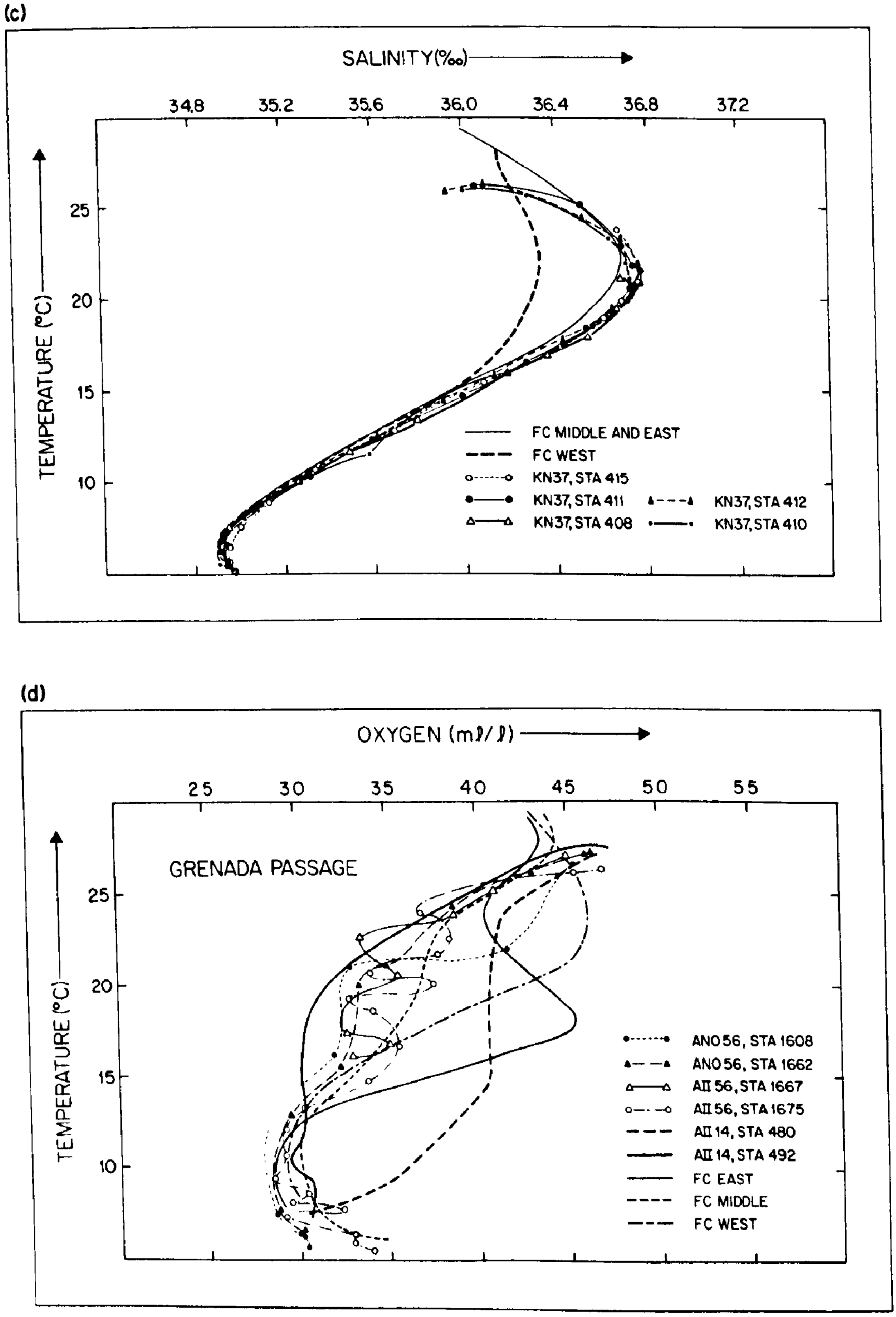

(c)
SALINITY(‰)
34.8
35.2
35.6
36.0
36.4
36.8
37.2
TEMPERATURE (°C)
25
20
15
10
FC MIDDLE AND EAST
FC WEST
KN37, STA 415
KN37, STA 411
KN37, STA 412
KN37, STA 408
KN37, STA 410
(d)
OXYGEN (ml/l)
25
30
35
40
45
50
55
GRENADA PASSAGE
TEMPERATURE (°C)
25
20
15
10
ANO 56, STA 1608
ANO 56, STA 1662
AII 56, STA 1667
AII 56, STA 1675
AII 14, STA 480
AII 14, STA 492
FC EAST
FC MIDDLE
FC WEST

Fig. 6. (cont.)

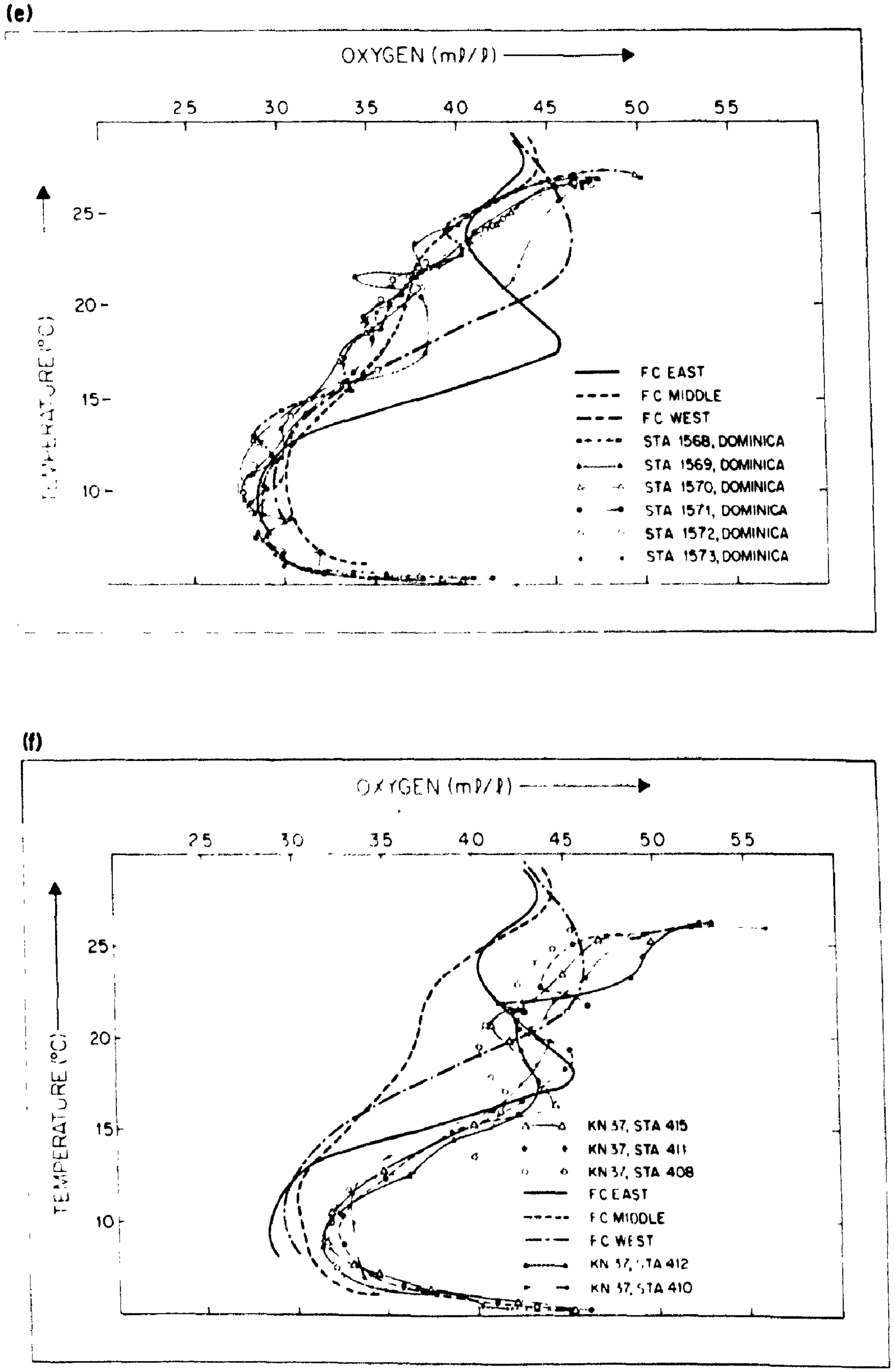

(e)
OXYGEN (ml/l)
25
30
35
40
45
50
55
TEMPERATURE (°C)
25
20
15
10
FC EAST
FC MIDDLE
FC WEST
STA 1568, DOMINICA
STA 1569, DOMINICA
STA 1570, DOMINICA
STA 1571, DOMINICA
STA 1572, DOMINICA
STA 1573, DOMINICA
(f)
OXYGEN (ml/l)
25
30
35
40
45
50
55
TEMPERATURE (°C)
25
20
15
10
KN 37, STA 415
KN 37, STA 411
KN 37, STA 408
FC EAST
FC MIDDLE
FC WEST
KN 37, STA 412
KN 37, STA 410

Fig. 6. (cont.)

Table 1. *Previous transport–temperature range partitioning*

Temperature range (°C)	Florida Current transport (Sv)*	Florida Current transport (Sv)†	Caribbean interior transport (Sv)‡	24°N transport (Sv)*
>17	17.4	19.3	17	−9.5
12–17	6.6	6.7	6	−2.9
7–12	5.0	3.9	6	1.9
<7	0.5	—	—	−19.0
Sum	29.5	29.5	29	−29.5

*Hall and Bryden (1982).
†Leaman *et al.* (1989).
‡Roemmich (1981).

however. Leaman (personal communication) attributes this difference primarily to varying methods of integration, including extrapolation (or not) between coastlines and last station, especially in the east. Molinari *et al.* (1985) found a transport of 30.5 Sv for the first year or so of the same data set.

In a more northerly but presumably mass-conserving region in the eastern North Atlantic, Stramma (1984) finds an upper ocean southward transport of 11 ± 1.5 Sv in roughly the same temperature range (>12°C) where HB 82 found 12.4 (Table 1), remarkable consistency indeed, and Saunders's (1982) results are similarly supportive. Roemmich and Wunsch (1985) are approximately in agreement with the basic HB 82 results along 24°N. The southward transport of 19 Sv at temperatures less than 7°C in Table 1 is presumably dominated by the Deep Western Boundary Current (DWBC); larger than Worthington (1976) proposes (see also Fine and Molinari, 1988) but in line with the measurements by Amos *et al.* (1971) and Lai (1984), and interestingly enough, with the Wüst (1957) estimate of ~20 Sv net southward abyssal transport in the South Atlantic. McCartney (personal communication) has recently found evidence for recirculation associated with the DWBC, particularly at tropical latitudes, with a few plausible net transport estimates of 10–15 Sv equatorward for water less than 5°C [see also Wunsch (1984), his Figs 6 and 7].

In Table 2, the partitioning of transport with temperature is for an expanded set of temperature ranges (numbers were interpolated from the indicated authors' raw data)

Table 2. *New transport–temperature range breakdowns*

Temperature range (°C)	Florida Current transport (Sv)*	Florida Current transport (Sv)†	Caribbean inflow transport (Sv)‡	24°N transport (Sv)*
>24	8.1	9.2	8.9	−1
17–24	9.3	10.0	8.4	−8.5
12–17	6.6	6.7	5.4	−2.9
7–12	5.0	3.9	6.1	1.9
<7	0.5	—	—	−19.0
Sum	29.5	29.8	28.8	−29.5

*Hall and Bryden (1982, recalculated).
†Leaman *et al.* (1989, recalculated).
‡New (recalculated).

relative to Table 1, chosen in light of the METCALF (1968) and SM 72 investigations, and in light of our explanation of how Fig. 1 applies. We will often refer to the T > 24°C water as the upper layer, the 12–24°C water as the mid-depth layer and use lower layer to denote 7–12°C water. The choices in Table 2 show that the uppermost layer (~50–100 m thick) transported in the F.C., ~8 Sv according to HB 82, has temperatures warmer than most of the 24°N surface water, i.e. >24°C. If there is no increase in upper ocean (>24°C) transport from the 24°N section (as analysed by HB 82) that flows south and presumably into the Caribbean and then through the Straits of Florida, we are seeking ~7 Sv of water warmer than 17°C (Table 1) or 24°C (Table 2) from a location other than across 24°N. We actually find, as described below, that 7.1 Sv of water >24°C is flowing from the South Atlantic through the Caribbean passages. Note that the 17–24°C water nearly balances between the F.C. and 24°N, and also for the Caribbean passages (Table 2). The objection to South Atlantic origin based on the T–O_2 curves in Fig. 1 does not apply to water above 24°C, because at the shallow depths involved (50–100 m) one can have "high" oxygen due to surface contact regardless of geographical origin. None of the F.C. transport in the 7–12°C range can be accounted for as moving south across 24°N according to HB 82, rather ~2 Sv is needed to flow north across 24°N (Table 2).

At this time, we also present a new breakdown of the direct transport measurements made by SM 72 for the Caribbean passages. SM 72 partitioned their transports with water properties somewhat differently (Table 3) than the other authors listed in Tables 1 and 2, so we have recalculated as described in some detail below the Caribbean passage

Table 3. Westward transport through the Grenada, St. Vincent and St. Lucia Passages as measured with a lowered current meter ($\times 10^6$ m^3 s^{-1})

Date	>36	O_2 minimum	<34.8	Total
Grenada Passage				
16 March	3.8	1.8	2.0	7.6
20 March	2.6	2.2	1.7	6.5
14 April	4.8	3.6	1.9	10.3
17 April	8.9	4.1	2.9	15.9
18 April	6.6	2.3	1.4	10.3
18 April	3.3	2.8	1.2	7.3
Mean	4.9	2.8	1.8	9.6
St. Vincent Passage				
22 March	4.1	5.4	3.2	12.7
23 March	4.6	5.8	1.7	12.1
26 March	3.5	3.6	1.7	8.8
10 April	3.8	2.7	1.2	7.7
12 April	4.3	2.6	1.2	8.1
13 April	4.7	2.6	1.7	9.0
Mean	4.1	3.8	1.8	9.7
St. Lucia Passage				
3 April	1.3	1.8	1.9	5.0
5 April	2.0	2.6	2.2	6.8
Mean	1.6	2.2	2.1	5.9
Grand means	10.6	9.0	5.7	25.2

allocations for the temperature ranges listed in Table 2. ROEMMICH (1981) partitioned his estimate of the transport through the Windward Passage with temperatures as well as for the western Caribbean and the totals listed in Table 1, and we have broken his estimates down further. The Anegada–Jungfern transports discussed by METCALF (1976) are not considered in detail at this time, as discussed below.

Transport–temperature allocations for the Caribbean passages individually are summarized in Table 4, with details of how we made the estimates in this table described in following sections. The critical sums in the last column of Table 4 are also listed in the next to last column of Table 2. Dominica Passage, included in Table 4 as well, is a special case that will be considered separately. In Table 4, the total transports (labeled Sum T) found by SM 72 are significantly larger (by 5.9 Sv) than the transports above 7°C (labeled Sum above 7, the Florida Current temperature range). This result will be discussed later, the point now being that the "extra" 5.9 Sv has temperatures lower than 7°C and salinities notably fresher than found in the F.C. (see also WORTHINGTON, 1976, Fig. 23, p. 60). It should be noted that the transport of ~19–20 Sv above 7°C (or ~700 m) is more in line with ROEMMICH (1981) than the 25 Sv considering all of the SM 72 layers in the southern passages. For the moment, please note that the (last) column in Table 4 containing total transports has 28.8 Sv of F.C. temperature range water moving through all the passages indicated. MAZEIKA *et al.* (1980) find a transport of 15 Sv relative to 700 db between Tobago and Barbados, essentially the same as our transport at T > 7°C through Grenada and St. Vincent Passages in Table 4 (first two columns). MODEL (1950) summarized Pillsbury's results to find 28–31 Sv of inflow into the Caribbean passages, consistent also with MONTGOMERY's (1941) estimate of 26–30 Sv for the Key West–Habana section in the western Straits of Florida. The distribution of passage transports listed by MODEL (1950) is different than that found by SM 72 or us, possibly an indicator of a time-dependent and complex circulation.

In Table 5, we have listed the summary of the South Atlantic transport results as tabulated by WÜST (1957, p. 417). These estimates are mean values based on the *Meteor* profiles at five latitudes and are split into regions east and west of the mid Atlantic ridge and into abyssal and upper ocean depth ranges. The net southward transport of water at

Table 4. New Caribbean Passage transport–temperature range results

Temperature range (°C)	Grenada Passage transport (Sv)*	St. Vincent Passage transport (Sv)*	St. Lucia Passage transport (Sv)*	Dominica Passage transport (Sv)	Windward Passage transport (Sv)†	Grand sums
>24	2.8	2.3	0.8	1.2	1.8	8.9
12–14	2.7	4.0	1.7	1.4	4.0	13.8
17–24	2.1	1.8	0.8	0.7	3.0	8.4
12–17	0.6	2.2	0.9	0.7	1.0	5.4
7–12	2.2	1.6	1.3	0.0	1.0	6.1
Sum above 7	7.7	7.9	3.8	2.6	6.8	28.8
<7	1.8	1.8	2.1	—	0.2	5.9
Sum T	9.5	9.7	5.9	2.6	7.0	34.7

*STALCUP and METCALF (1972).
†ROEMMICH (1981).

Table 5. Net transport in the South Atlantic based on Meteor *profiles, according to* WÜST (1957)

Western Trough*		Eastern Trough*	
0–1400 m	7.0 Sv	0–1200 m	15.8 Sv
1400–3750 m	−27.5 Sv	1200–5000 m	4.8 Sv
3750–5000 m	2.0 Sv		

+ is northwards, − southwards.

*Depth range, followed by total transports for the indicated depths.

depths greater than 1400 m in the west and 1200 m in the east is 22.8 Sv, close to HB 82's southerly transport of 19 Sv in this depth range at 24°N. WÜST's (1957) transports in the 0–200 m depth range are ~35 to 40% (see his pp. 370–380) of the total northward upper ocean flow, i.e. 7–9 Sv, as found by us and listed in Tables 2 and 4 for the uppermost layer.

4. THE NEAR-SURFACE (>24°C) FLOW

All investigators agree that roughly 8–9 Sv is flowing in the F.C. in the upper 100 m (nominal), at temperatures greater than 24°C (Table 2, also see RICHARDSON *et al.*, 1969; HB 82; LEAMAN *et al.*, 1989). HB 82 found a southerly transport of only 1 Sv for water warmer than 24°C along 24°N (Table 2). The near-surface temperatures along 24°N between the Bahamas and Africa are typically a few degrees colder than the near-surface temperatures in the tropical Atlantic, Caribbean, and Florida Straits (see any temperature chart, e.g. EMERY, 1983, his Fig. 7a). Upper level salinities in the F.C. (Fig. 2) are in the range 35.8–36.0, fresh relative to water from the North Atlantic Gyre, as shown by Fig. 7 (adapted from WORTHINGTON, 1976), a map of salinity at 30 m depth. Salinities lower than 36.0 in Fig. 7 (Fig. 7a shows the whole North Atlantic, Fig. 7b more detail from the tropical Atlantic) penetrate from the eastern South and Equatorial Atlantic into the North Atlantic and the Caribbean, as do the surface temperatures in EMERY's (1983, p. 279) map, partially included here in smoothed form in Fig. 8. WÜST (1957) has roughly 16 Sv of upper ocean water headed north (Table 5) on the east side of the South Atlantic (his depth range is 0–1200 m). The 7 Sv or so that he has flowing in the upper 200 m may be reflected in Figs 7 and 8. Most of the surface water along 24°N is the high salinity (~36.5–37.0) water called Subtropical Underwater or Salinity-Maximum Water that WORTHINGTON (1976) has sinking and intruding to the south as a subsurface salinity maximum near 150 m depth. Figures 7 and 8 are comparatively clear indicators of surface flow from the eastern South Atlantic toward the Caribbean. This pattern is broad, with the tongues in temperature and salinity in close proximity, and not restricted to be near the North Brazil Coast.

Table 3 is an adaption of SM 72's transport table for the Caribbean passages, with the mean total transport listed as well, averaged over all section occupations. The minor number of free-fall instrument results are not listed, nor are the few estimates in Dominica Passage. In Table 3, transport measurements for the three indicated Caribbean passages and dates of observation were split by SM 72 into three layers defined by the 36.0 and 34.8 isohalines. We need to determine the relationship of SM 72's three layers to the ones used

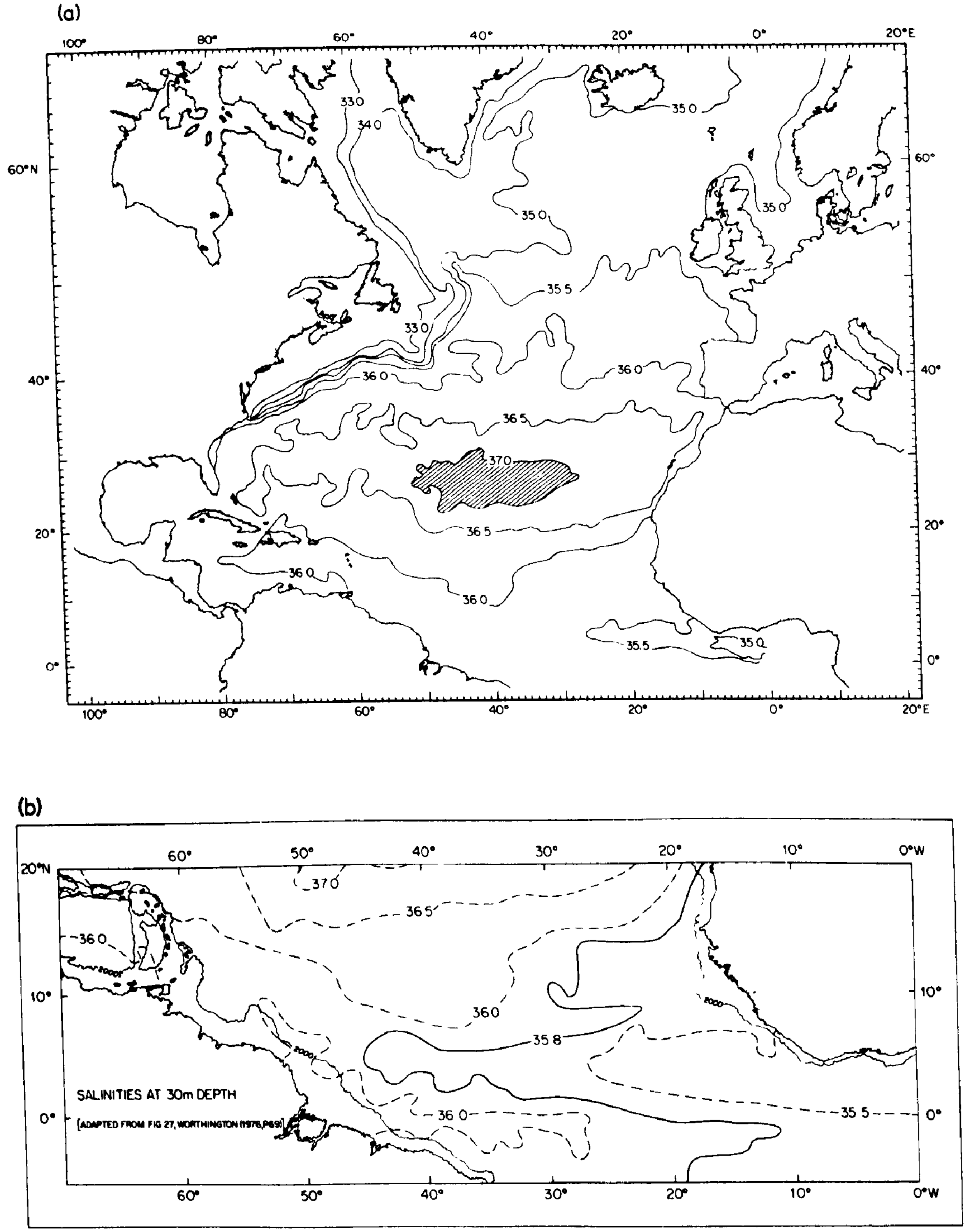


Fig. 7. Upper level (at 30 m depth) salinity map, adapted from WORTHINGTON (1976, p. 69); (a) for the North Atlantic, large-scale, (b) for the tropical Atlantic.

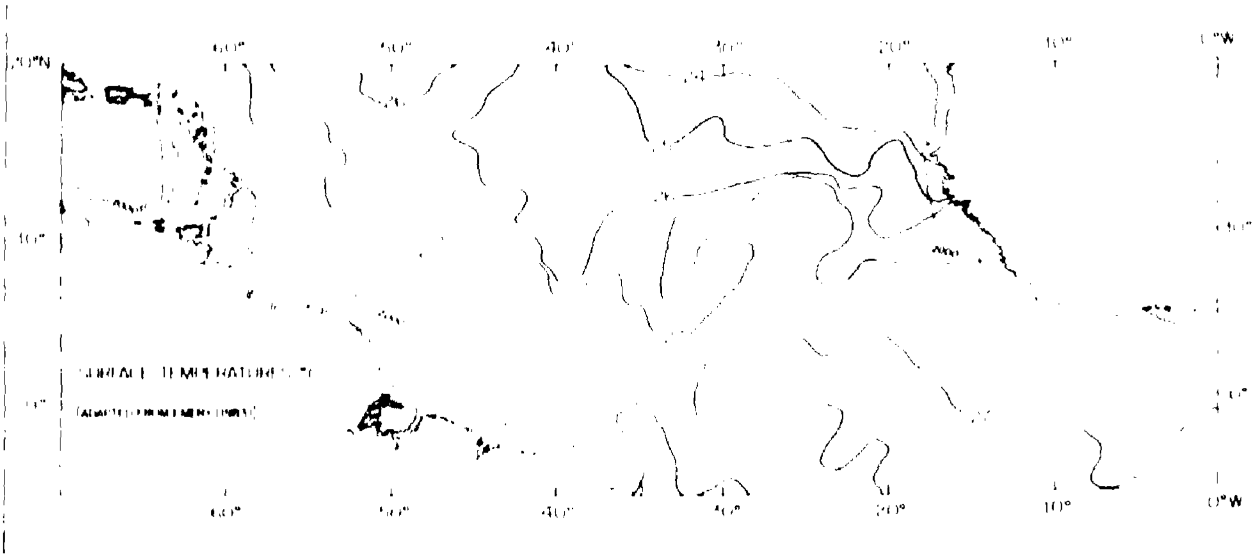


Fig. 8. Surface temperature map for the tropical Atlantic, adapted from EMERY (1983).

in Tables 1 and 2, as defined by the temperature ranges >24, 12–24 and 7–12°C. We also split the 12–24°C layer into two pieces.

Figure 9 is a plot of selected speed contours normal to the section shown in Grenada Passage for one observation period (19–20 March 1970), based on Fig. 3 in SM 72 and the data in STALCUP *et al.* (1971). A strong near-surface (upper 50–100 m) current in the Grenada Passage is clearly depicted in Fig. 9. Speeds are larger than 2 kn in the core, a jet-

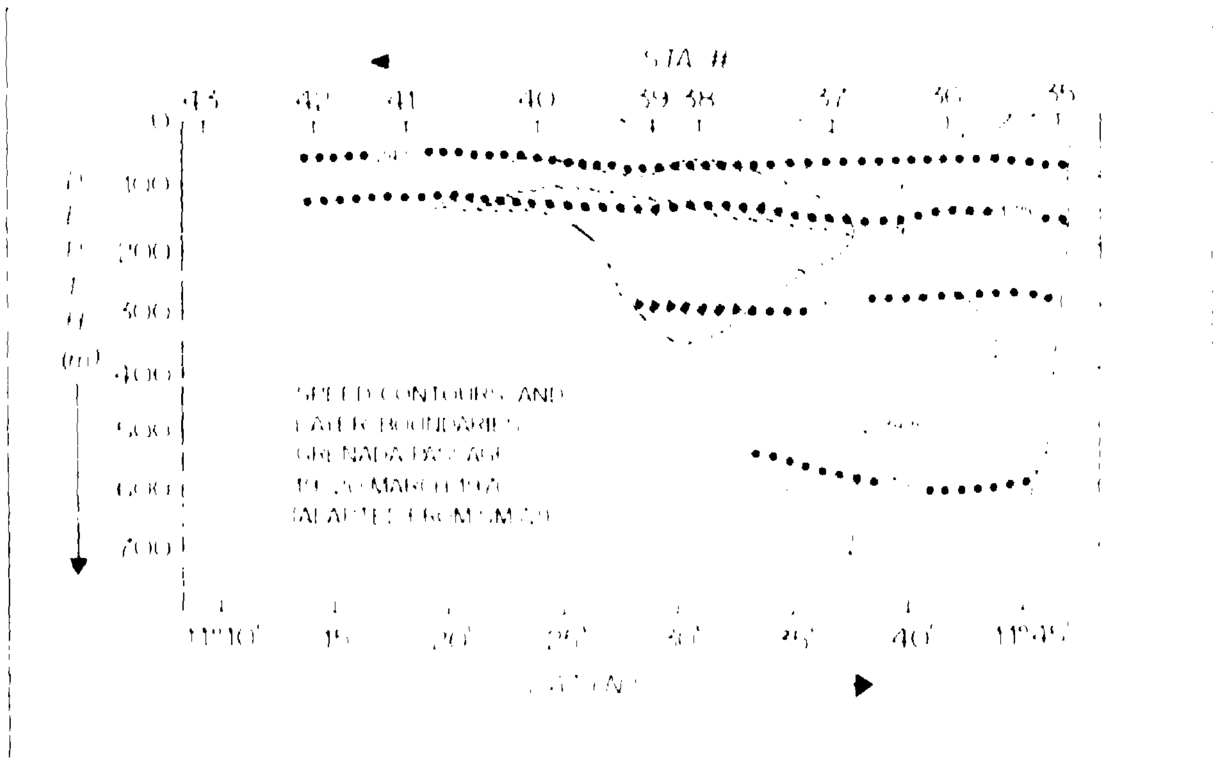


Fig. 9. Speed contours and layer boundaries (selected isotherms and isohalines) in the Grenada Passage. March 1970 data, taken from STALCUP and METCALF (1972).

like flow similar to that expected for an extension of the Guiana Current. The near-surface salinities in the Caribbean passages are typically 35.8–36.0 in the SM 72 data (see for detail Stalcup *et al.*, 1971; Metcalf *et al.*, 1971), about the same as for the F.C. in Fig. 2.

Figure 9 also indicates the location of the 36.0 and 34.8 isohalines, as plotted by SM 72, as well as the location of the 7, 12, 17 and 24°C isotherms (temperature and salinity section for the Grenada Passage are contained in Fig. 10). The 7 and 17°C isotherms are at roughly the analogous locations as the SM 72 upper and lower layer boundaries, the deepest 36.0 and the 34.8 salinity contours. For St. Vincent Passage the 7°C isotherm is closer to the 34.8 isohaline and the 17°C isotherm is further from the 36.0 isohaline than for Grenada Passage, and St. Lucia is in the middle. For an upper layer boundary of 24°C (instead of the 36.0 salinity contour in Fig. 9) the uppermost layer transport for the relevant dates is calculated to be 1.7 instead of 2.6 Sv. If this relative change for one section is applied to the Grand Means in Table 3, then the average transport in Grenada Passage at temperatures greater than 24°C would be 2.8 Sv (Table 4). By also recalculating the flow in the same manner for particular sections through St. Vincent (Fig. 11) and St. Lucia Passages, we end up with 2.3 and 0.8 Sv as mean transports, respectively, for the T > 24°C layer.

The composite Grand Mean based on these and analogous Grenada Passage data is 5.9 Sv (Table 4) for our upper layer in the three southern passages. By making a similar estimate using Roemmich's (1981) results for the Windward Passage (see below), we get 1.8 Sv flowing in through the T > 24°C layer there. The Grand Mean of 7.7 Sv for the composite upper layer transport through the four passages (Table 4) noted above is 1.5 Sv smaller than the estimated T > 24°C transport in the F.C. according to Leaman *et al.* (1989) and nearly the same as that found by HB 82 (Table 2).

5. THE NEAR-BOTTOM (7–12°C) FLOW

The 7–12° range salinities are somewhat fresh for the southern Caribbean passages and Anegada, and slightly salty for Windward, relative to the standard F.C. curve. A map (adapted from Worthington, 1976) of salinity on the 10°C isotherm, roughly the mid-point of our 7–12°C layer, is consistent with low salinity water penetrating from the South Atlantic (Fig. 12). However, the T–S curve for the F.C. in the 7–12° range is closer to that for Windward Passage than for the southern passages, as pointed out by Worthington (1976, p. 70). As far as we know, the 7–12° T–S curves in the Yucatan Channel as well as the F.C. are much more alike than those across the Caribbean passages. An inspection of the available data suggests to us that the silicate in the 7–12° range in the F.C. could come from the eastern South Atlantic, where oxygens are low (as needed).

The 34.8 isohaline lower boundary for SM 72's layer 2 (upper boundary of their layer 3) is convenient for our purposes. From Fig. 2, no water with a salinity lower than 34.8 flows through the Straits of Florida. The 7°C isotherm is at roughly the same depth as the 34.8 isohaline and may therefore be chosen as the lower boundary of our lowest layer. This is a better estimate for St. Vincent and St. Lucia Passages than for Grenada. With this approximation the flow (Table 4) through the southern three passages that can enter the Straits of Florida is approximately 19.6 out of the total of 25.2 Sv found by SM 72 to be flowing into the Caribbean. This observation ameliorates the difference noted by Roemmich (1981) relative to his and the SM 72 results. Metcalf (1976) has suggested that at least some of the deep inflow measured by SM 72 not exiting through the Florida Straits could be exiting the Caribbean through Anegada–Jungfern Passage.

We find that of the 6.5 Sv observed by SM 72 (Table 3) to flow through Grenada Passage (Fig. 9 indicates layer limits) on 19–20 March 1970 in their three layers, respectively (2.6, 2.2, 1.7), only 4.8 (the sum of their upper two layers) enter the Straits of Florida. With our choice of layers (>24, 12–24 and 7–12°C) the partitioning of this 4.8 is (1.7, 1.7, 1.4) Sv. For St. Vincent on 10 April we get (1.9, 3.3, 1.3) instead of (3.8, 2.7, 1.2) and for St. Lucia

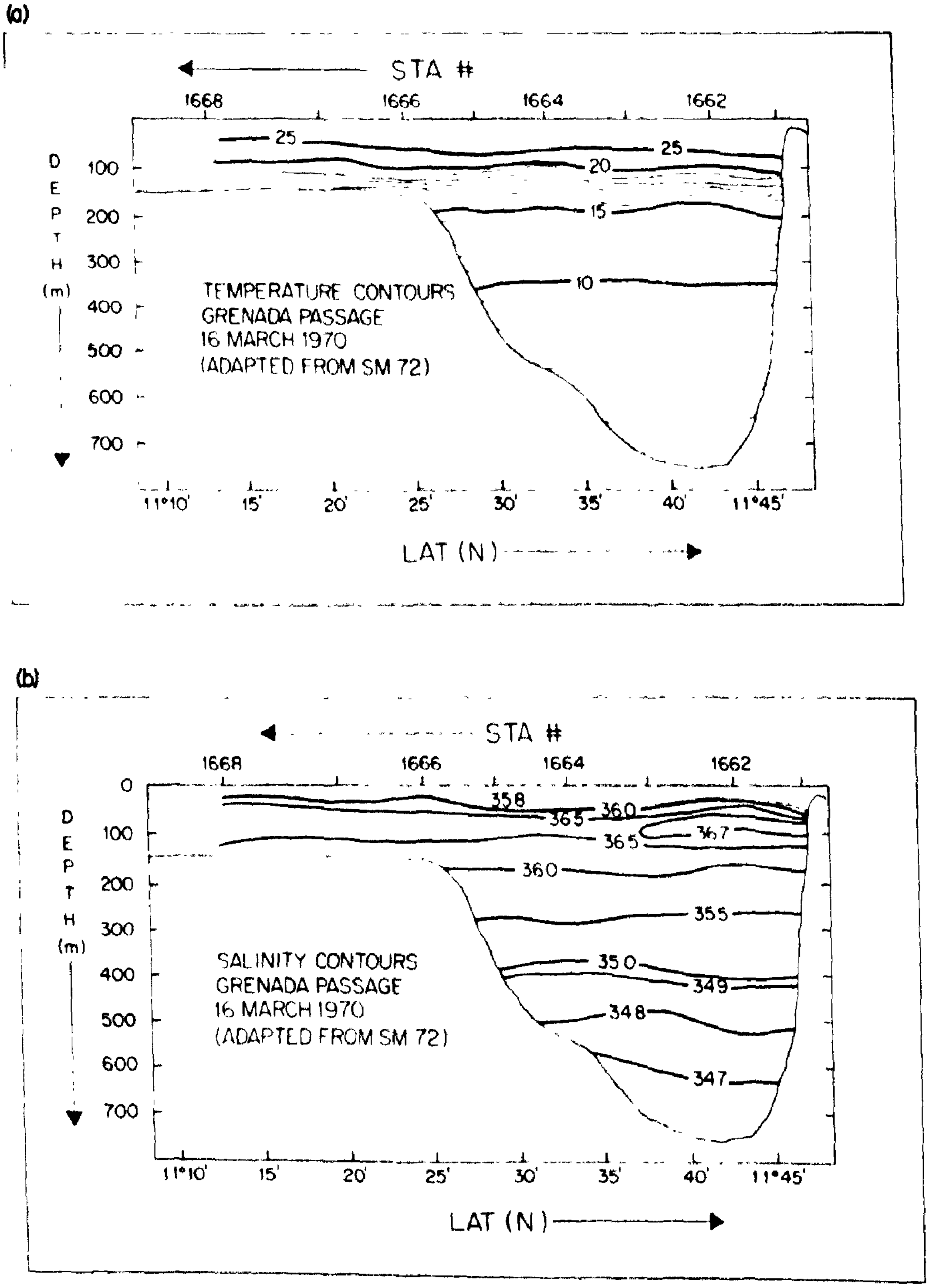


Fig. 10. (a) Temperature (T) and (b) salinity (S) sections for the Grenada Passage, after SM 72.

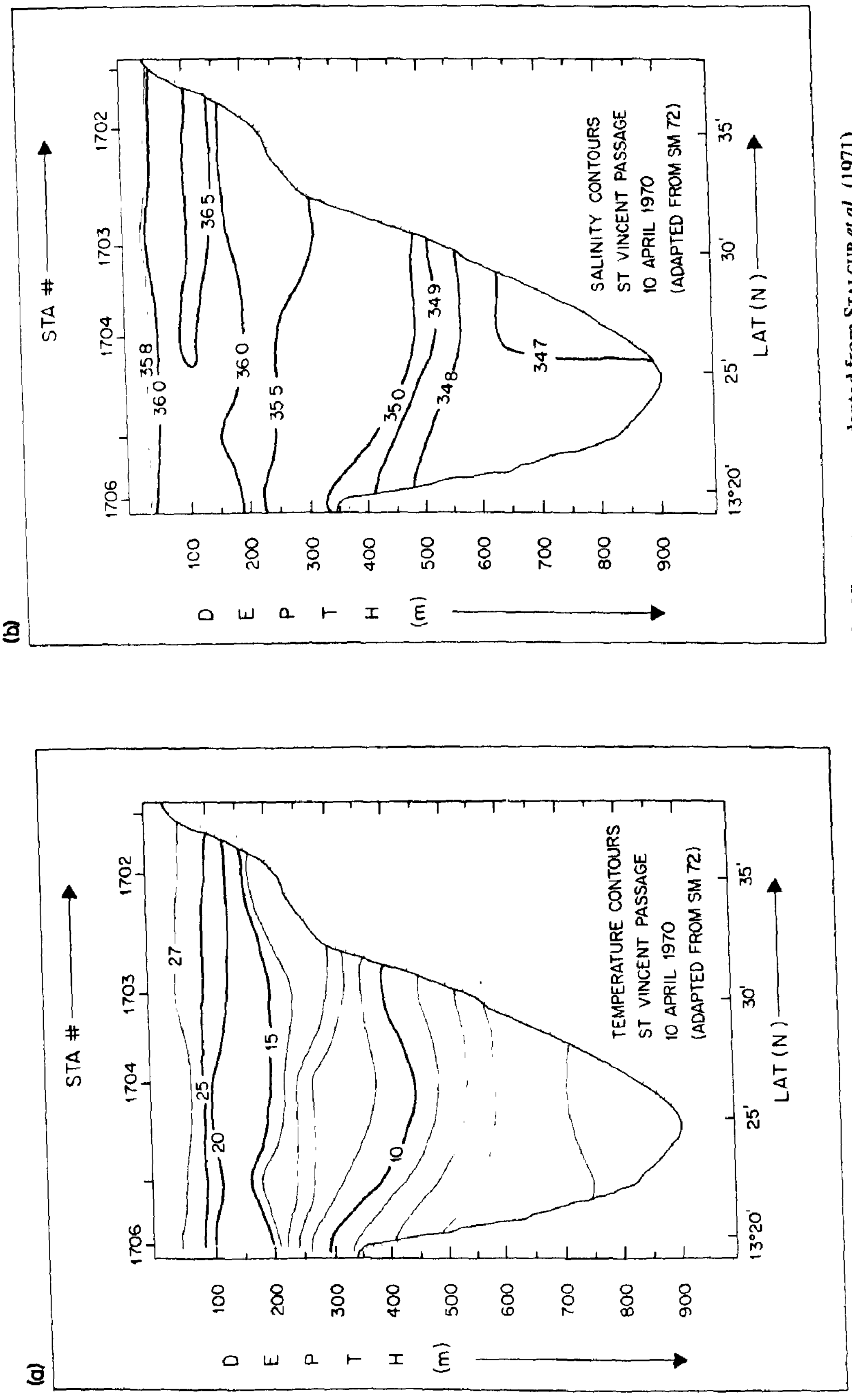


Fig. 11. (a) Temperature (T) and (b) salinity (S) sections for the St. Vincent passage, adapted from Stalcup *et al.* (1971).

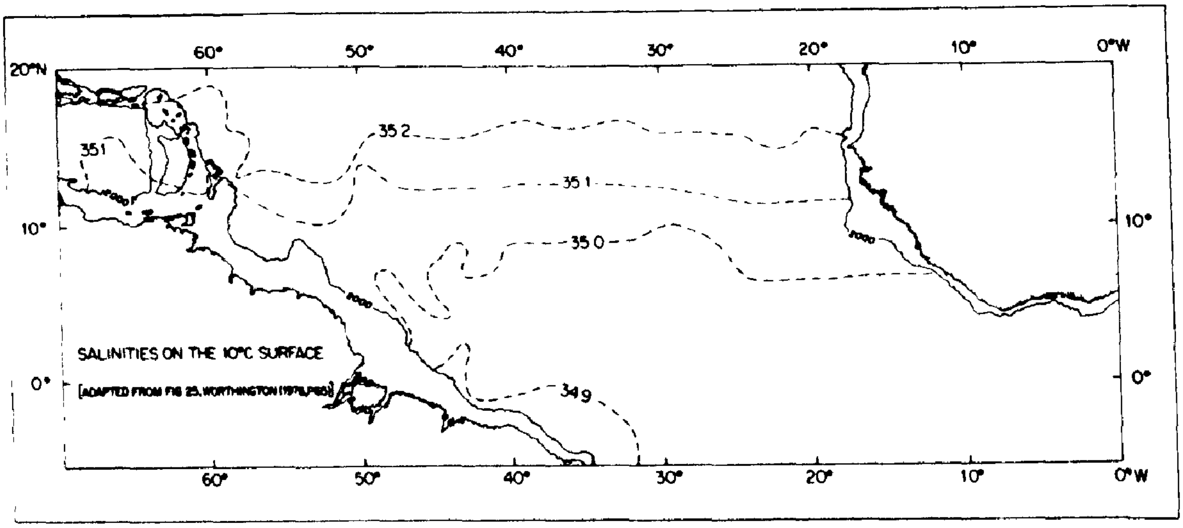


Fig. 12. Salinity on the 10°C temperature surface, adapted from WORTHINGTON (1976, p. 69)

Passage on 5 April (1.0, 2.0, 1.6) instead of (2.0, 2.6, 2.2). For the 7–12°C layer in the Windward Passage we get 1.0 Sv, following ROEMMICH (1981), with 4.0 Sv flowing in through the 12–24°C layer, to go along with the 1.8 in the surface (>24°C) layer. If the percentage changes for the 7–12°C layer are applied to Grand Means from individual sections as we did for the surface layer, then the cold water transport through the three southern passages is (2.2, 1.6, 1.3) for Grenada, St. Vincent and St. Lucia, respectively. So our total 7–12°C transport at this stage (Table 4) is 6.1 Sv, ~1 Sv larger than the HB 82 result for the F.C. (Table 2), 2 Sv larger than the LEAMAN *et al.* (1989) estimate, and essentially the same as ROEMMICH's (1981) result.

6. THE MID-DEPTH (12–24°C) FLOW

Using the same techniques as described previously for the other layers, the 12–24°C composite Grand Mean transport (Table 4) through the three southern passages occupied by SM 72 is from south to north, (2.7, 4.0, 1.7) Sv, a total of ~8.4 Sv, about 7–8 Sv less than found for the F.C. (Tables 1 and 2). There are 4 Sv flowing into the Caribbean through Windward Passage in the 12–24°C layer based on ROEMMICH's (1981) results (speed contours are in Fig. 13a). NOF and OLSON (1983) have tabulated (their Table 1, p. 1953) the results of several estimates of the transport through Windward Passage. Except for GORDON (1967), these transports vary between 7 and 15 Sv. T–S and T–O_2 characteristics similar to the eastern side of the Straits of Florida (Fig. 2) are found in the Windward Passage (Figs 13b,c), especially for 18° Water. The flow of 18° Water through the Windward Passage is the main source (see also Fig. 6a) we have identified for the 18° Water found in the Straits of Florida. We also split the 12–24°C layer into two pieces for the southern three passages by noting that the SM 72 choice of >36‰ as the lower boundary of their upper layer is approximately the same as choosing the 17°C isotherm as this boundary. In Windward Passage we use ROEMMICH's (1981) breakdowns. All these results are in Table 4.

7. DOMINICA PASSAGE

Our total transport through the three southern passages into the Caribbean (Table 4) at temperatures warmer than 7°C (~19–20 Sv) is about 2–3 Sv less than the 22 Sv found by Roemmich (1981) for the western Caribbean. Similarly, our F.C. total with 7 Sv from Windward and not including Dominica Passage is ~26 rather than the expected ~30 Sv. Also we are 3–4 Sv short of 12–24°C water at this point.

Although a few Sverdrups do not represent a large discrepancy, it appears as if some of the flow could be originating in Dominica Passage in Roemmich's Fig. 8 (1981). So we recalculated the results for this passage, where SM 72 found 3.3 and −0.7 Sv (the convention is + in and − out of the Caribbean, as in Table 4) on 8 and 9 April 1972, respectively. Surprisingly we found 2.5 and 2.7 Sv at $T > 7°C$ (essentially $T > 12°C$) for these two sections, which were made at different orientations (the geometry of this passage is very complex) but apparently calculated the same. This point has been examined in detail with M. C. Stalcup, who agrees. The temperature range breakdown for the average of these numbers is (1.2, 1.4, 0.0) Sv for our three standard layers, as listed in Table 4.

8. SUMMARY AND CONCLUSIONS

We have examined new direct measurements of currents (transport) and temperature in the Florida Current and combined and contrasted them with old data in the Florida Straits, in the Caribbean passages, along 24°N, in the tropical Atlantic and in the South Atlantic. The total transports in the Florida Current and Caribbean passages balance to within ~1 Sv and transport–temperature partitioning is shown to be consistent to within ~2 Sv in four vertical layers (Table 2). We recompute the total transport into the Caribbean passages to be 28.8 Sv for the temperature range appropriate to the Straits of Florida off Miami. Five passages are found to contribute: Grenada (7.7 Sv), St. Vincent (7.9 Sv), St. Lucia (3.8 Sv), Dominica (2.6 Sv), and Windward (6.8 Sv). We have not explicitly considered Anegada Passage in detail because the data there are of different character from the other five passages noted above. Also, our interpretation of the T–O_2 curves on the Atlantic and Caribbean sides of Anegada Passage in Fig. 14 is that 18° Water is not flowing in through this passage, suggesting a different reference level than used by Metcalf (1976). In addition, the high salinities observed in the core of subtropical underwater here are not found in the Florida Current. We strongly recommend future observational programs in this passage.

Most of the near-surface flow of water in the Straits of Florida is notably less saline as well as warmer than surface water at equivalent latitudes in the North Atlantic and likely originates in the eastern South Atlantic. "Surface water" in the Atlantic north of the Caribbean is observed to the south as Salinity–Maximum Water or Subtropical Underwater under a warmer lens in the tropics that is 50–100 m deep. Of the 8.9 Sv moving through the Florida Current with temperatures above 24°C in depth range of 50–100 m, 7.1 Sv is composed of comparatively fresh warm water coming through the southern Caribbean passages from the tropical South Atlantic. Saltier surface water, 1.8 Sv, enters from the North Atlantic through Windward Passage as does the 18° Water for the Florida Current. A South Atlantic origin for the contribution from the upper 50–100 m is fairly clear-cut because the surface water in the Atlantic north of the Caribbean is cold and salty and intrudes or is subducted south below a comparatively warm and fresh layer 50–100 m

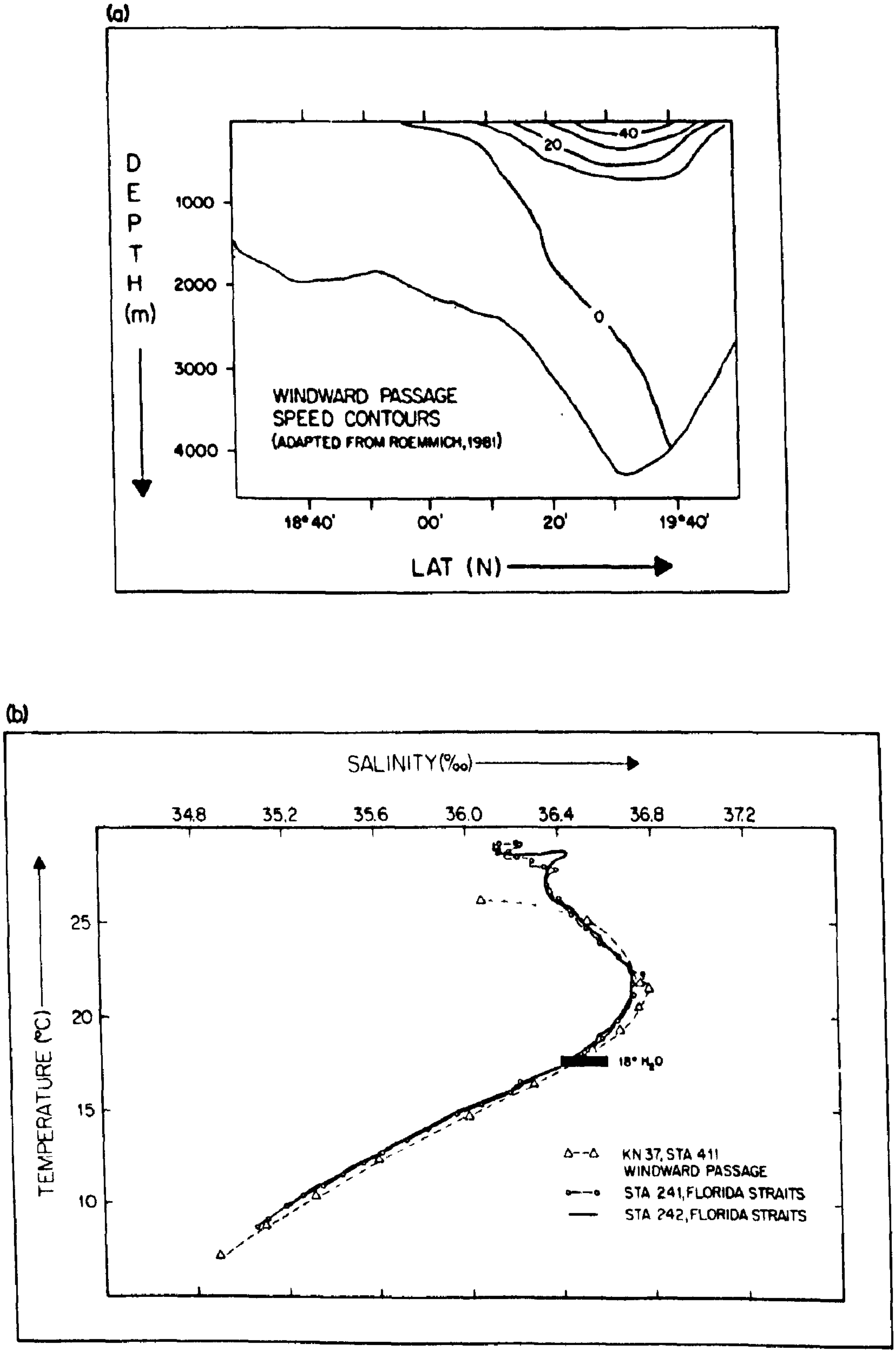


Fig. 13. Windward Passage: (a) speed contours (cm s^{-1}), adapted from ROEMMICH (1981), (b) T–S plot for the station in the center of the current in (a) in comparison with stations on the eastern side of the Florida Current, (c) corresponding T–O_2 plots.

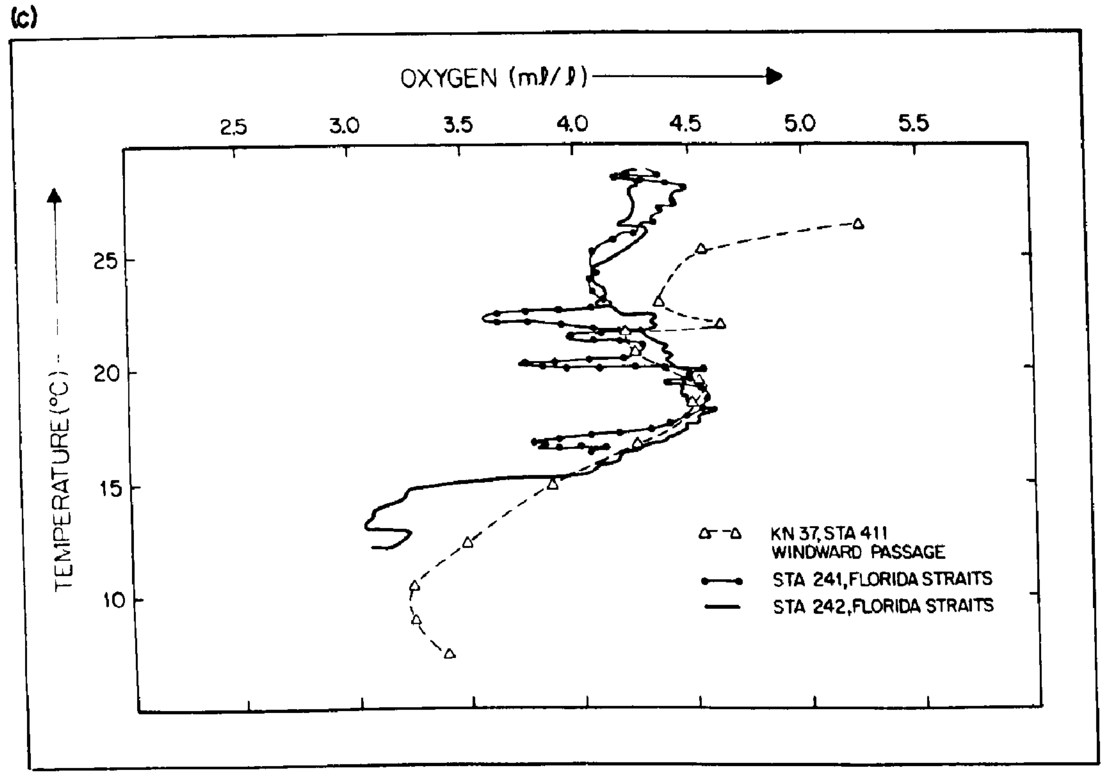


Fig. 13. (cont.)

thick, which could not be transported from the North Atlantic. Of the 13.8 Sv transported into the Caribbean in the 12–24°C temperature range, 13.0 Sv is probably of North Atlantic origin, with 0.8 Sv of comparatively fresh South Atlantic water flowing on the western side of the Florida Straits, having entered the Caribbean on the southern side of St. Vincent and St. Lucia Passages. Of the 6 Sv transported by the Florida Current in the 7–12°C temperature range, 5 Sv could have originated in the South Atlantic.

Of the Florida Current transport 13 Sv or 45% (~30 Sv total) may originate in the South Atlantic, as compensation for the flow of North Atlantic Deep Water across the equator. These results strongly support, independently, the original suggestion of cross-equatorial exchange made by Stommel (1957), and later supported by Hall and Bryden (1982) and Gordon (1986). In simple terms, we are essentially saying that flow from the North Atlantic mostly penetrates the Caribbean passages and Florida Current as either 18°C Water or as Salinity-Maximum Water between a surface layer and 7–12°C water, the latter two flows being primarily from the South Atlantic. Parr (1937a, p. 91, last sentence) concluded for the Caribbean circulation that a maximum salinity layer of Sargasso Sea origin injects itself between the surface layer and deeper water masses derived from the east and south. This picture is also consistent with Worthington's Figs 35–40 (1976, pp. 86–91) and the majority of other references with which we are familiar. The sum of the pioneering work by Metcalf and Stalcup in the tropical Atlantic demonstrated that most of the warm water in the 12–24°C temperature range flowing into the North Atlantic along the coast of South America returns toward the South Atlantic, especially in forming the

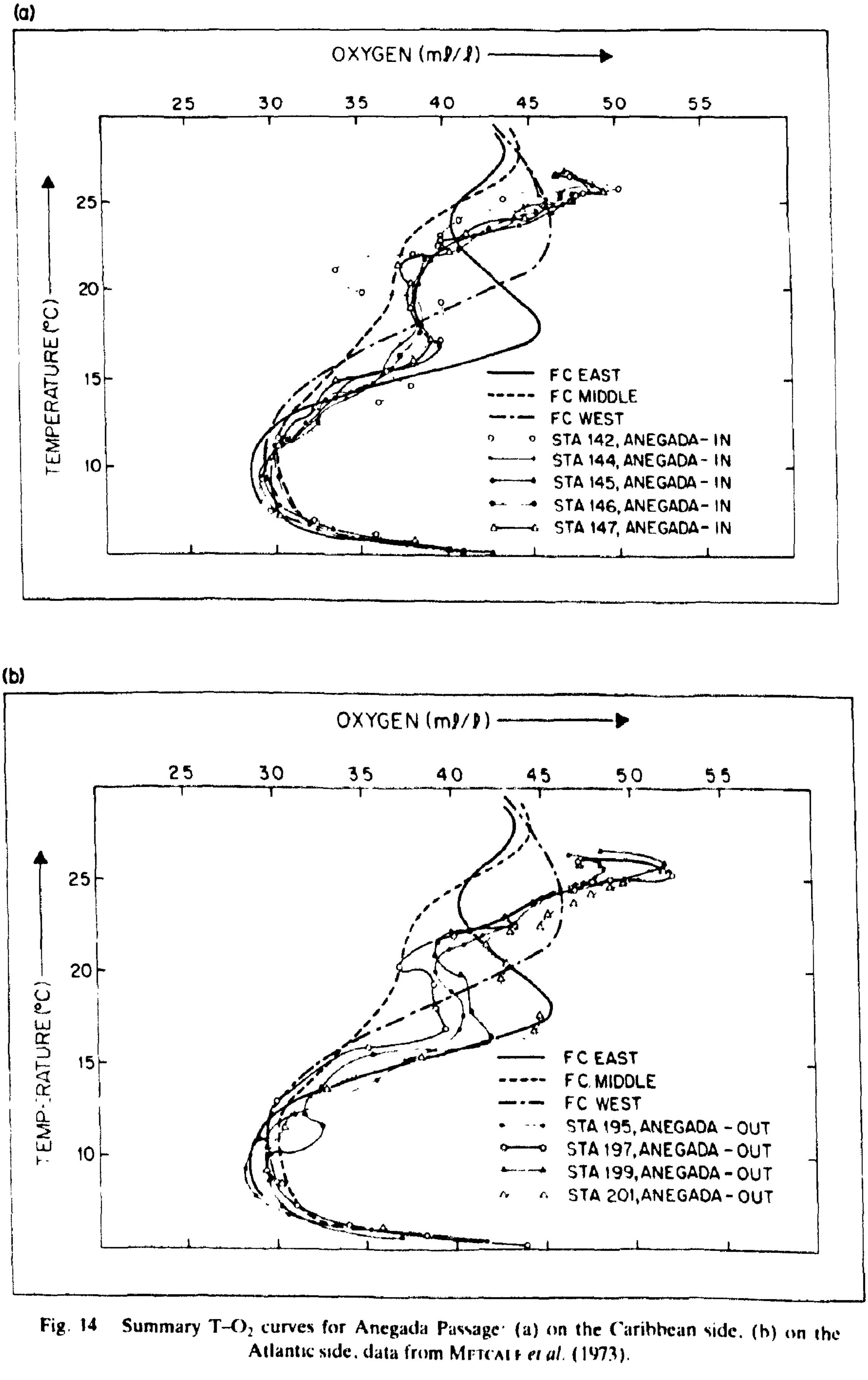


Fig. 14 Summary T–O_2 curves for Anegada Passage: (a) on the Caribbean side, (b) on the Atlantic side, data from Metcalf *et al.* (1973).

Equatorial Undercurrent (Metcalf and Stalcup, 1967) and is the origin of the contemporary picture of retroflection and "separate" North Brazil Coastal Current and Guiana Current Systems (Boyd, 1986; Flagg *et al.*, 1986). We reiterate this conclusion, finding that 95% of the Florida Current transport in the 12–24°C temperature range is of North Atlantic origin. However, roughly 80% (a total of 13.0 Sv) of the remaining Florida Current transport in lower and higher temperature ranges is from the South Atlantic, consistent with the observation that the essential water mass restriction in the 12–24°C range does not apply either to the ventilated near-surface waters in the upper 50–100 m of the tropical Atlantic, where temperatures are greater than 24°C, or for temperatures less than 12°C.

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REFERENCES

Amos A. F., A. L. Gordon and E. D. Schneider (1971) Water masses and circulation patterns in the region of the Blake–Bahama Outer Ridge. *Deep-Sea Research*, **18**, 145–165.

Boyd J. D. (1986) Thermohaline steps off the northeast coast of South America. Ph.D. Dissertation, Texas A&M University, College Station, Texas, 171 pp.

Cochrane J. D. (1963) Equatorial undercurrent and related currents off Brazil in March and April 1963. *Science*, **142**, 669–671.

Cochrane J. D. (1969) Low sea-surface salinity off northeastern South America in summer 1964. *Journal of Marine Research*, **27**, 327–334.

Cochrane J. D., F. J. Kelley and C. R. Olling (1979) Subthermocline countercurrents in the western equatorial Atlantic Ocean. *Journal of Physical Oceanography*, **9**, 724–738.

Emery W. J. (1983) On the geographical variability of the upper level mean and eddy fields in the North Atlantic and North Pacific. *Journal of Physical Oceanography*, **13**, 269–291.

Fine R. A. and R. L. Molinari (1988) A continuous deep western boundary current between Abaco (26.5°N) and Barbados (13°N). *Deep-Sea Research*, **35**, 1441–1450.

Flagg C. N., R. L. Gordon and S. McDowell (1986) Hydrographic and current observations on the continental slope and shelf of the western equatorial Atlantic. *Journal of Physical Oceanography*, **16**, 1412–1429.

Froelich P., D. Atwood and G. Geise (1978) Influence of Amazon River discharge on surface salinity and dissolved silicate concentrations in the Caribbean. *Deep-Sea Research*, **25**, 735–744.

Gibbs R. J. (1970) Circulation in the Amazon River estuary and adjacent Atlantic Ocean. *Journal of Marine Research*, **28**, 113–121.

Gordon A. L. (1967) Circulation of the Caribbean Sea. *Journal of Geophysical Research*, **72**, 6207–6223.

Gordon A. L. (1986) Interocean exchange of thermocline water. *Journal of Geophysical Research*, **91**, 5037–5046.

Gordon A. L. and A. R. Piola (1983) Atlantic Ocean upper layer salinity budget. *Journal of Physical Oceanography*, **13**, 1293–1300.

Hall M. M. and H. L. Bryden (1982) Direct estimates and mechanisms of ocean heat transport. *Deep-Sea Research*, **29**, 339–359.

Lai D. Y. (1984) Mean flow and variabilities in the Deep Western Boundary Current. *Journal of Physical Oceanography*, **14**, 1488–1498.

Leaman K. D., R. L. Molinari and P. S. Vertes (1987) Structure and variability of the Florida current at 27°N: April 1982–July 1984. *Journal of Physical Oceanography*, **17**, 565–583.

Leaman K. D., E. Johns and T. Rossby (1989) The average contribution of volume transport and potential vorticity with temperature at three sections across the Gulf Stream. *Journal of Physical Oceanography*, **19**, 36–51.

Mazeika P. A., D. A. Burns and T. H. Kinder (1980) Mesoscale circulation east of the southern Lesser Antilles. *Journal of Geophysical Research*, **85**, 2743–2758.

Metcalf W. (1968) Shallow currents along the northeastern coast of South America. *Journal of Marine Research*, **26**, 232–243

Metcalf W. G. (1976) Caribbean–Atlantic Water exchange through the Anegada–Jungfern Passage. *Journal of Geophysical Research*, **81**, 6401–6409.

Metcalf W. and M. Stalcup (1967) Origin of the Atlantic Equatorial Undercurrent. *Journal of Geophysical Research*, **72**, 4959–4975.

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 Oceanographic Institution Technical Report, WHOI-71-13, 103 pp.

Metcalf W. G., M. C. Stalcup and M. Zemanovic (1973) Hydrographic station data, Caribbean Sea, *Knorr* Cruise 25. Woods Hole Oceanographic Institution Technical Report, WHOI-73-10, 133 pp.

Metcalf W. G., M. C. Stalcup and M. Zemanovic (1974) Hydrographic station data, Caribbean Sea, *Atlantis II* Cruise 78 and *Knorr* Cruise 37. Woods Hole Oceanographic Institution Technical Report, WHOI-74-90, 148 pp.

Metcalf W. G., M. C. Stalcup and M. Zemanovic (1977) Current meter and temperature records from the Windward Passage. Woods Hole Oceanographic Institution Technical Report, WHOI-77-29, 33 pp.

Model V. F. (1950) Pillsburys Strommessungen und der Wasserhaushalt des Amerikanischen Mittelmeeres. *Deutsche Hydrographische Zeitschrift*, **3**, 57–61.

Molinari R. L., W. D. Wilson and K. D. Leaman (1985) Volume and heat transports of the Florida Current: April 1982 through August 1983. *Science*, **227**, 295–297.

Montgomery R. B. (1941) Transport of the Florida Current off Habana. *Journal of Marine Research*, **4**, 198–220.

Muller-Karger F. E., C. R. McClain and P. L. Richardson (1988) The dispersal of the Amazon's water. *Nature*, **333**, 56–59.

Neumann G. (1969) Seasonal salinity variations in the upper strata of the western tropical Atlantic Ocean. I. Sea surface salinities. *Deep-Sea Research*, **16**(Suppl.), 165–177.

Nof D. and D. B. Olson (1983) On the flow through broad gaps with application to the Windward Passage. *Journal of Physical Oceanography*, **13**, 1940–1956.

Parr A. E. (1935) Report on hydrographic observations in the Gulf of Mexico and the adjacent straits made during the Yale oceanographic expedition on the "*Mabel Taylor*" in 1932. *Bulletin of the Bingham Oceanographic Collection*, **5**(1), 93 pp.

Parr A. E. (1937a) A contribution to the hydrography of the Caribbean and Cayman Seas, based upon the observations made by the Research Ship "*Atlantis*" 1933–34. *Bulletin of the Bingham Oceanographic Collection*, **5**(4), 110 pp.

Parr A. E. (1937b) Report on hydrographic observations at a series of anchor stations across the Strait of Florida. *Bulletin of the Bingham Oceanographic Collection*, **6**(3), 62 pp.

Richardson P. L. and G. Reverdin (1987) Seasonal cycle of velocity in the Atlantic North Equatorial Countercurrent as measured by surface dirfters, current meters, and ship drifts. *Journal of Geophysical Research*, **92**, 3691–3708.

Richardson W. S., W. J. Schmitz, Jr and P. P. Niiler (1969) The velocity structure of the Florida Current from the Straits of Florida to Cape Fear. *Deep-Sea Research*, **16**, 225–231.

Roemmich D. (1981) Circulation of the Caribbean Sea: a well-resolved inverse problem. *Journal of Geophysical Research*, **86**, 7993–8005.

Roemmich D. and C. Wunsch (1985) Two transatlantic sections: meridional circulation and heat flux in the subtropical North Atlantic Ocean. *Deep-Sea Research*, **32**, 619–664.

Saunders P. M. (1982) Circulation in the eastern North Atlantic. *Journal of Marine Research*, **40**, Suppl., 641–657.

Schmitt R. W., H. Perkins, J. D. Boyd and M. C. Stalcup (1987) C-SALT: an investigation of the thermohaline staircase in the western tropical North Atlantic. *Deep-Sea Research*, **34**, 1655–1665.

Schmitz W. J., Jr and W. S. Richardson (1968) On the transport of the Florida Current. *Deep-Sea Research*, **15**, 679–693.

Stalcup M. C. and W. G. Metcalf (1972) Current measurements in the passages of the Lesser Antilles. *Journal of Geophysical Research*, **77**, 1032–1049.

Stalcup M. C., W. G. Metcalf and M. Zemanovic (1971) Current measurements in the Lesser Antilles. Woods Hole Oceanographic Institution Technical Report, WHOI-71-51, 78 pp.

STALCUP M. C., W. G. METCALF and R. G. JOHNSON (1975) Deep Caribbean inflow through the Anegada–Jungfern Passage. *Journal of Marine Research*, **33**, Suppl., 15–35.

STOMMEL, H. (1957) A survey of ocean current theory. *Deep-Sea Research*, **4**, 149–184.

STRAMMA L. (1984) Geostrophic transport in the warm water sphere of the eastern subtropical North Atlantic. *Journal of Marine Research*, **42**, 537–558.

WENNEKENS M. P. (1959) Water mass properties of the Straits of Florida and related waters. *Bulletin of Marine Science of the Gulf and Caribbean*, **9**, 1–52.

WORTHINGTON L. V. (1959) The 18° Water in the Sargasso Sea. *Deep-Sea Research*, **5**, 297–305.

WORTHINGTON L. V. (1976) On the North Atlantic Circulation. *The Johns Hopkins Oceanographic Studies*, No. 6, The Johns Hopkins University Press, 110 pp.

WUNSCH C. (1984) An eclectic Atlantic Ocean circulation model. Part I: The meridional flux of heat. *Journal of Physical Oceanography*, **14**, 1712–1733.

WÜST G. (1957) Quantitative untersuchungen zur statik und dynamik des Atlantischen Ozeans, Stromgeschwindigkeiten und strommengen in den tiefen des Atlantischen Ozeans unter besonderer berücksichtigung des tiefenund bodenwassers. *Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf dem Forschungs- und Vermessungsschiff "Meteor" 1925–1927*, **VI**, 261–420.

WÜST G. (1964) *Stratification and circulation in the Antillean–Caribbean Basins; Part One, spreading and mixing of the water types with an oceanographic atlas*, With assistance of Arnold Gordon, Columbia University Press, New York, 201 pp.