The Net Transport of the Antarctic Circumpolar Current through Drake Passage

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ABSTRACT

Estimates of the net transport through Drake Passage are made for three periods during which the year-long DRAKE 79 current meter array spanning the Passage was in operation. Relative geostrophic shears from hydrographic surveys in January 1979, April 1979 and January 1980 were referenced to direct speed measurements to give profiles of net speed. Direct measurements were averaged in time to make them more compatible with the spatially-averaged baroclinic shears. The agreement between directly-measured and baroclinic shears is generally good except in regions of large bathymetric relief and during periods when current cores were shifting past or between moorings.

The presence of cold-core rings during two of the DRAKE 79 hydrographic surveys resulted in intensified flow and increased transport within fronts, but did not affect the net transport through the Passage. The three latest estimates of net transport (117, 144 and 134 $\times 10^6$ m^3 s^{-1}) are in close agreement with a previous estimate of 124 $\times 10^6$ m^3 s^{-1} made from 1975 data using the same technique. The consistency of these four estimates suggests that the net transport may be less variable than some previous calculations have implied.

1. Introduction

A major goal of the International Southern Ocean Studies (ISOS) program is to understand the dynamical balance involved in driving the Antarctic Circumpolar Current (ACC). Before the importance of the various components of the dynamical balance can be specified, we must be able to measure accurately the response of the ACC to whatever is forcing it. In a gross sense, the total transport of the ACC is a time- and space-integrated measure of the response of the system to all forcing mechanisms. The magnitude of the transport must ultimately be related to the strength of the forcing, and transport fluctuations to changes in the forcing. With transport measurement one of its goals, ISOS began a series of field programs called the First Dynamic Response and Kinematic Experiments (FDRAKE) in 1975 to lay the groundwork for a major sampling and monitoring experiment DRAKE 79 which was conducted between January 1979 and February 1980.

The results of the initial ISOS field experiment (FDRAKE 75) showed that the ACC transport is not evenly distributed across Drake Passage, but concentrated in three fronts which separate four distinct water mass zones (Nowlin *et al.*, 1977, hereinafter referred to as NWP). Emery (1977) has shown that the fronts are continuous from south of Australia to Drake Passage, and Whitworth (1980) has used historical hydrographic data to estimate the relative transport associated with the fronts. Most of the ACC transport is associated with the two northern fronts, the Subantarctic Front and the Polar Front, and a smaller portion of the total transport is within the Continental Water Boundary at the southern extreme of the Passage.

Reid and Nowlin (1971) pointed out that the pressure field in Drake Passage appears to be quite stable in time, and NWP compared relative geostrophic transport calculations from FDRAKE 75 and 76 to five earlier cruises. We update this comparison in Table 1 which gives the transport above and relative to 3000 db for seven sections across the passage near a line connecting Cape Horn and Livingston Island in the South Shetland group.

Reid and Nowlin (1971) calculated the net transport through Drake Passage by using direct current measurements to provide reference speeds for relative geostrophic transports. Their net transport estimate, based on nine hydrographic stations and five current records of 1–4 days duration, was 237 $\times 10^6$ m^3 s^{-1}. Foster (1972) estimated a transport of -15×10^6 m^3 s^{-1} (westward) using 10-day current records from three meters on each of four moorings. NWP combined Foster's direct current measurements with hydrographic data taken on the same cruise to obtain a transport of between -26×10^6 m^3 s^{-1} (westward) and 11 $\times 10^6$ m^3 s^{-1} (eastward) depending on which current meters were used. The disparity in these estimates can be attributed in large part to mooring separations which were too large to sample adequately the current variations across the ACC. Sciremammano *et al.* (1980) calculated the spatial scales of velocity fluctuations using the first zero-crossing of the cross-correlation function between current meters. They estimated that the cross-passage scale

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TABLE 1. Geostrophic transport (10^6 m^3 s^{-1}) above and relative to 3000 db for ISOS stations spanning Drake Passage.

Melville 1975 (section II)	111
(section V)	106
Thompson 1976	110
Melville 1977	75
Melville 1979	110
Yelcho 1979	102
Atlantis II 1980	105
Mean	103
Standard deviation	12.6

of the through-passage velocity fluctuations is on the order of 40 km.

NWP estimated net transports using two hydrographic sections and 13 moorings separated by ~50 km. The component of velocity normal to the hydrographic section was averaged for a three-week period to provide reference speeds for the relative transport calculations. Four moorings had more than one current meter and hence more than a single reference speed. For these moorings, transports were calculated relative to each instrument and averaged. The net transport for their most densely sampled hydrographic section was 124×10^6 m^3 s^{-1}.

A major goal of the DRAKE 79 experiment was to refine further our estimate of net transport through Drake Passage. Consequently, the design of the moored array reflected several results from previous experiments which we expected to improve transport estimates. Moorings in the northern and central passage were separated by a nominal 45 km. This spacing was expected better to resolve the estimated 30–40 km widths of the Subantarctic and Polar fronts, which together account for nearly 60% of the relative transport through Drake Passage (Nowlin and Clifford, 1982). Mooring separations in the southern Passage, which is characterized by slower flow, were ~65 km. To sample better the near-surface flow, all moorings were instrumented at 500 m as well as at 2500 m.

In this paper we make three independent estimates of the net transport of the ACC through Drake Passage by referencing hydrographic data from three cruises to the currents measured by the DRAKE 79 moored array. We will also consider the problem of how best to reconcile measured currents and calculated geostrophic speeds.

2. DRAKE 79 measurements

The DRAKE 79 moored array was deployed in January 1979 from R.V. *Melville* and recovered in February 1980 from R.V. *Atlantis* II. Hydrographic surveys were conducted during these cruises and also during April–May 1979 from the Chilean ship AGS *Yelcho*. The main-line (ML) array (Fig. 1) consisted of 17 moorings on a line between Cape Horn and Livingston Island. A seven-mooring mapping and statistics (MS) array was located west of the ML moorings along the historical mean position of the Polar Front. All Aanderaa current meters were equipped to record temperature and pressure, and five instruments also had conductivity sensors. The current meter data are reported by Pillsbury *et al.* (1981). Pressure gages were placed at the 500 and 2500 m isobaths at each side of the Passage.

The data return for the main-line array is indicated in Fig. 1. Most of the recovered instruments returned a full record of over a year's duration. The most serious losses were main-line moorings 3 and 4. Although the acoustic releases for moorings 3, 4 and 8 failed, three of the uppermost instruments were recovered by dragging. Mooring motion, due to large current speeds, caused occasional pressure-record losses as the instruments were pulled below the design depth for the pressure sensors.

The hydrographic station plan was the same for all three cruises and consisted of stations between the ML moorings and a grid of stations over a region including the MS array and adjacent ML moorings. Samples were taken from the surface to the bottom along the main-line and to a depth of ~2500 m within the MS array.

3. Reference-speed determination

In principle, the calculation of net transport is straightforward: geostrophic speed and transport are calculated relative to some depth at which actual speed is measured; adding the measured reference speed to the relative geostrophic shear gives an adjusted speed profile from which net transport can be calculated. In practice, the reference speed and relative geostrophic speed suffer compatibility problems. The relative geostrophic speed is a quasi-synoptic spatial average of the flow perpendicular to two hydrographic stations. Even if the internal pressure field does not change during the sampling period, the relative speed is representative of the actual speed only to the extent that the actual flow is geostrophic—and this is unknown. The current-meter speeds, on the other hand, are point measurements rather than spatial averages and contain an entire spectrum of motions, ageostrophic as well as geostrophic. The high-frequency ageostrophic motions need not be considered since they are effectively removed with a low-pass filter (40 h half-power point) and the time series is re-sampled at 6 h intervals. We assume that the remaining long-period fluctuations in the current records are geostrophic except near continental boundaries and in regions of rough bottom topography. By averaging the low-passed current records over some period of time ending at the time of the hydrographic station pair, we should be able to reconcile the direct measurements with the relative speeds.

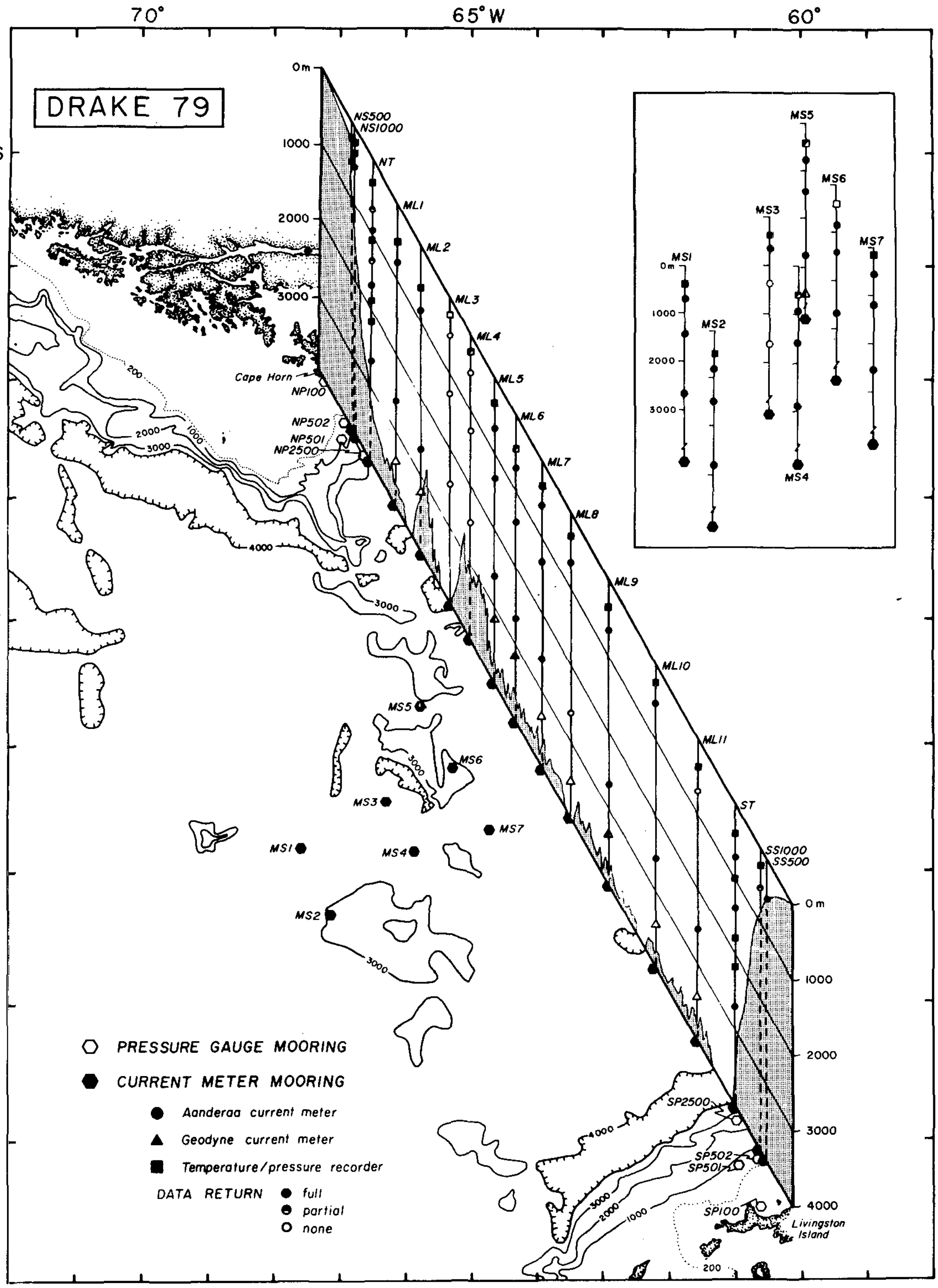

FIG. 1. Schematic representation of DRAKE 79 moored array indicating instrument locations and data return.

The appropriate averaging length for the current records depends on both the time and space scales of the features being measured. In Drake Passage there are two distinct types of flow: the three fronts are relatively narrow, have large vertical shears and are known to undergo wavelike oscillations and rapid lateral shifts in position; the zones between fronts are broad, of more uniform density and are characterized

TABLE 2. Agreement between directly-measured speeds and baroclinic shear as a function of the length of time over which the direct measurements were averaged. The values give the range of the differences (cm s^{-1}) between measured speed and baroclinic shear relative to 2500 db. Ranges of less than 5 cm s^{-1} are underlined and the optimum averaging period is boxed.

Mooring	Cruise	Number of current meters	Averaging length							
			6 h	1 day	3 days	5 days	7 days	10 days	15 days	20 days
	M	(5)	32.2	27.0	38.0	34.9	39.1	44.0	—	—
NT	Y	(5)	7.3	10.1	7.5	9.2	4.2	3.9	3.1	4.2
	A	(3)	5.2	10.3	14.7	7.9	15.4	19.9	20.4	18.9
	M	(2)	17.9	14.9	6.1	1.8	0.7	3.2	—	—
ML1	Y	(2)	1.3	0.8	7.0	6.4	3.6	1.5	0.1	3.1
	A	(2)	4.3	19.4	34.7	28.3	26.9	24.4	21.6	23.8
	M	(1)	—	—	—	—	—	—	—	—
ML2	Y	(2)	5.9	4.3	3.1	2.4	1.9	2.1	2.4	1.7
	A	(2)	1.7	1.5	2.6	3.2	3.0	0.1	3.9	5.8
	M	(4)	4.5	4.0	3.2	5.0	7.2	—	—	—
ML5	Y	(4)	3.7	2.9	5.3	6.1	8.8	7.2	3.1	5.2
	A	(2)	0.8	0.2	0.8	1.3	1.3	1.3	1.9	0.6
	M	(4)	5.4	4.8	3.8	—	—	—	—	—
ML6	Y	(3)	2.7	4.1	5.7	4.6	5.4	8.2	13.1	15.9
	A	(4)	4.2	4.5	6.8	7.5	7.9	8.0	7.7	7.0
	M	(3)	6.4	1.8	5.2	7.5	—	—	—	—
ML7	Y	(3)	5.2	5.2	5.8	3.4	2.9	5.1	7.8	7.9
	A	(2)	1.0	1.2	0.8	0.2	0.3	0.4	0.5	1.5
	M	(2)	3.1	5.1	—	—	—	—	—	—
ML9	Y	(3)	5.3	3.8	2.4	2.5	2.5	2.7	3.8	3.4
	A	(2)	1.6	1.8	1.9	1.8	1.7	1.4	1.0	0.8
	M	(2)	1.2	1.3	1.2	—	—	—	—	—
ML10	Y	(2)	0.7	1.5	1.5	1.4	0.7	0.1	0.4	0.5
	A	(2)	0.4	0.4	0.1	0.1	0.2	1.0	1.0	2.0
	M	(3)	2.4	2.1	—	—	—	—	—	—
ST	Y	(3)	2.8	4.7	6.5	7.3	6.9	6.8	7.1	6.9
	A	(3)	7.3	6.2	3.4	5.1	6.3	7.2	8.1	9.5

by slower speeds. The spacing of the hydrographic stations is about the same as the mooring spacing (45 km in the north and central passage—65 km in the south). The fronts are generally smaller in scale, 20–40 km (Nowlin and Clifford, 1982), so that a pair of hydrographic stations may span both a front and a current-meter mooring while the mooring is not in the high-speed core of the front. If a front remains fixed in space, the current meter may never record speeds typical of the high-speed core. If a front shifts laterally or experiences some wavelike oscillation, it may wander directly over the mooring. In this case, a time average of the current as it wiggles over the mooring is similar to a spatial average. The optimum averaging period will differ from mooring to mooring depending on the hydrographic conditions. In regions of sluggish flow, away from fronts, the averaging period should not be critical if the flow is relatively steady. Near fronts, the averaging period is dependent on the motion of the front relative to the mooring and may need to be very short or quite long for an adequate representation of the flow. As in NWP, we have compared the directly measured currents on moorings with more than one instrument to the baroclinic shear from hydrographic stations spanning the mooring to determine the appropriate averaging period.

If the directly measured currents were purely geostrophic, the component of speed perpendicular to the hydrographic station pair $u(z, t)$ would be offset

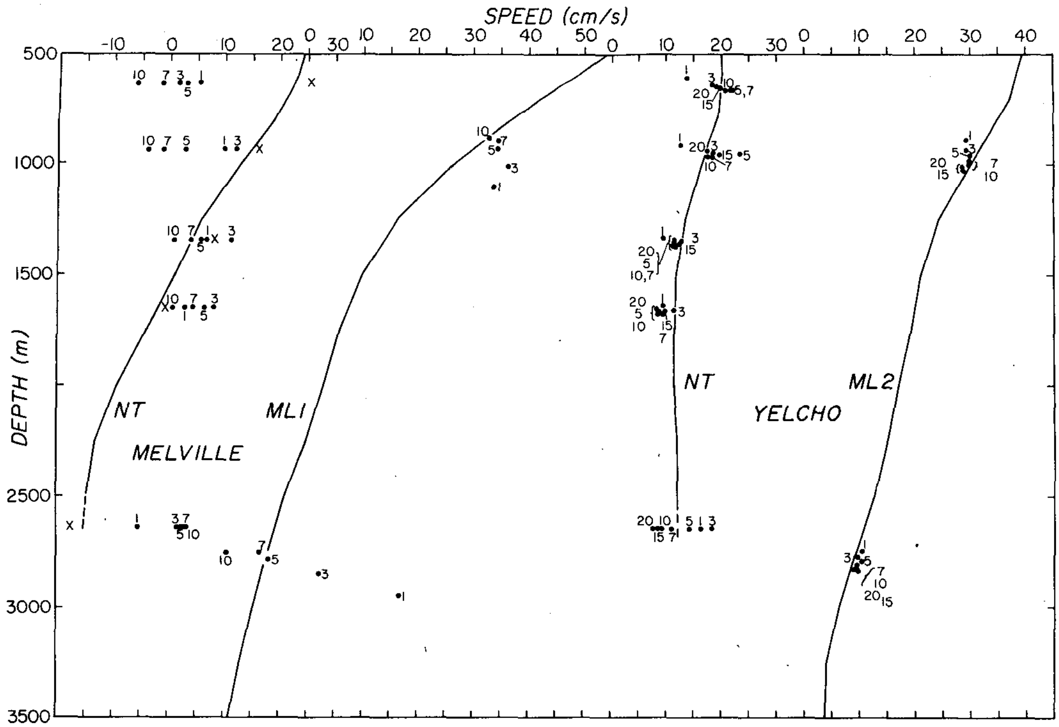

FIG. 2. Measured and calculated speeds at northern Drake Passage moorings during two DRAKE 79 cruises. Direct measurements, averaged for the number of days indicated, are shown as dots. The continuous curve is the relative baroclinic shear, which has been offset to match the direct measurements. The ×'s by the NT mooring for the *Melville* cruise show direct measurements from a 6 h period one week after the hydrographic section (see text).

by a constant from the baroclinic shear $u_b(z, t)$. The amount of the offset depends on the reference level for the geostrophic speeds. In this paper, the geostrophic speeds will be calculated relative to 2500 db and the offset will be referred to as the reference speed. To quantify the offset, we have calculated $\Delta u(t) = u_b - u$ for each current meter on a mooring. The value of $u(t)$, hence of $\Delta u(t)$, depends on the averaging period for the direct measurements.

Because the current meters do not measure just geostrophic motions, $\Delta u(t)$ will be different for different instruments on the same mooring. A measure

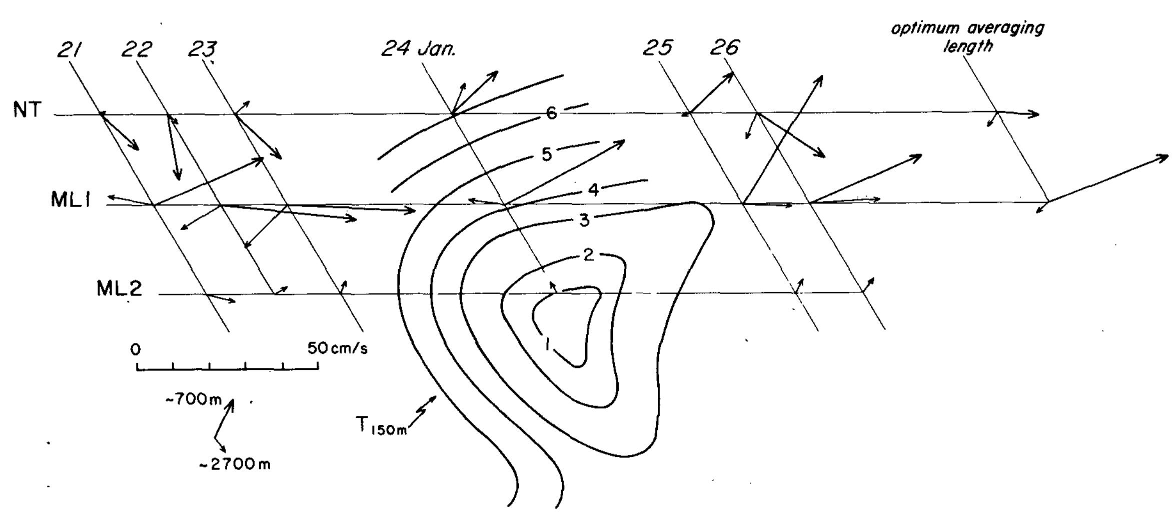

FIG. 3. Daily-averaged current vectors at three moorings in the northern Drake Passage during the R.V. *Melville* cruise. Isotherms at 150 m from an XBT survey on 24 January show a cold-core ring near mooring ML2. The vectors for the averaging period which produces best agreement between measured and calculated shears are shown on the right.

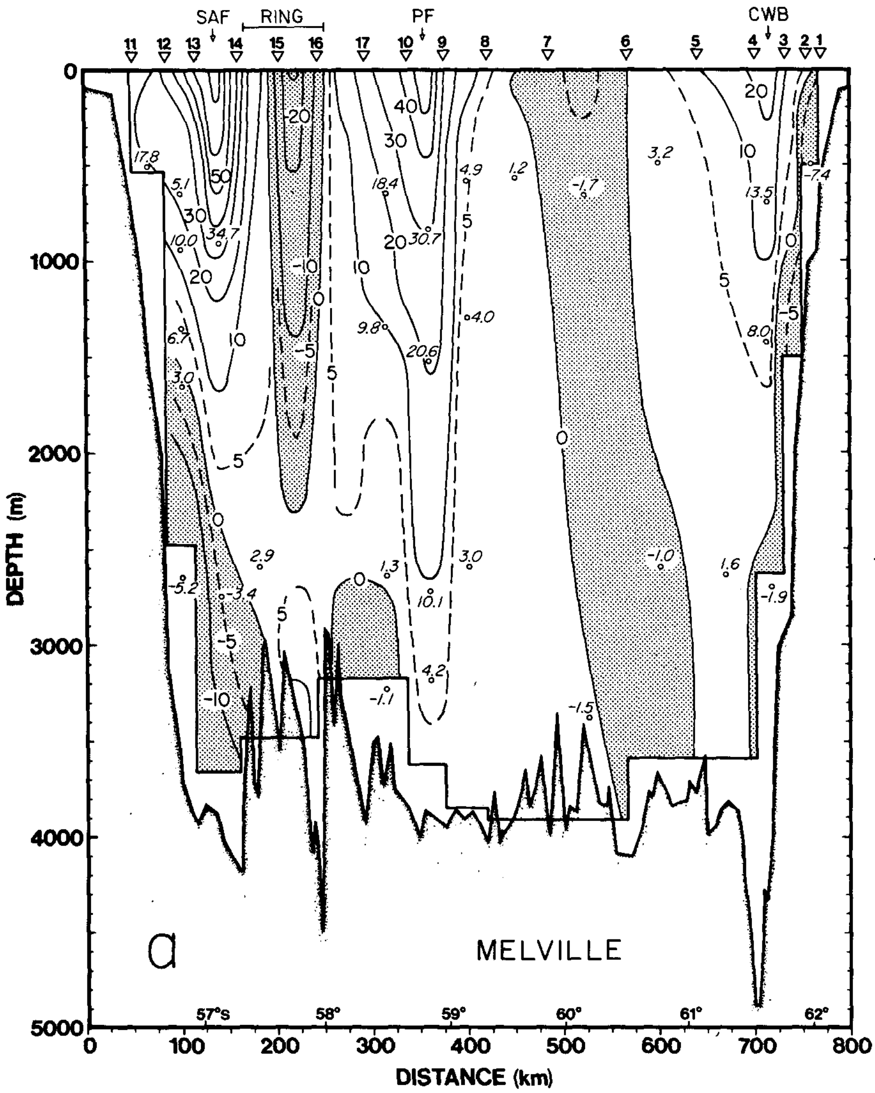

FIG. 4. Vertical sections of net geostrophic speed (cm s^{-1}) for DRAKE 79 cruises aboard (a) *Melville*, (b) *Yelcho* and (c) *Atlantis* II. The values shown for direct speed measurements (circles) are averages for that period of time that produces best agreement with baroclinic shears. SAF = Subantarctic Front, PF = Polar Front, CWB = Continental Water Boundary.

of the agreement between directly measured and baroclinic speeds is the range of Δu for a particular averaging period, i.e., $\Delta u_{max} - \Delta u_{min}$. The range of Δu relates the agreement in shears to transport: the cross-sectional area between hydrographic stations multiplied by the range of Δu for each averaging length gives the difference in net transport which will result from referencing relative transport to the direct measurements.

Table 2 gives the range of Δu as a function of averaging length for each mooring during the three hydrographic cruises. Ranges of less than 5 cm s^{-1} are underscored and the value representing the optimum averaging period is boxed. In most cases, the optimum period selected is the absolute minimum in the range of u, but in a few cases, we have selected a relative minimum at a shorter averaging period. (Although the choice of a relative minimum is somewhat subjective, the resulting difference in transport is relatively insensitive to the choice—never exceeding 6×10^6 m^3 s^{-1}.) Agreement with baroclinic shear is best for short averaging lengths for most moorings. For some moorings, especially those in the southern passage, the flow is steady enough that the averaging period makes little difference. In the north, the flow is highly variable and the choice of averaging length becomes more important. At NT, for example, agreement is poor regardless of averaging period for the

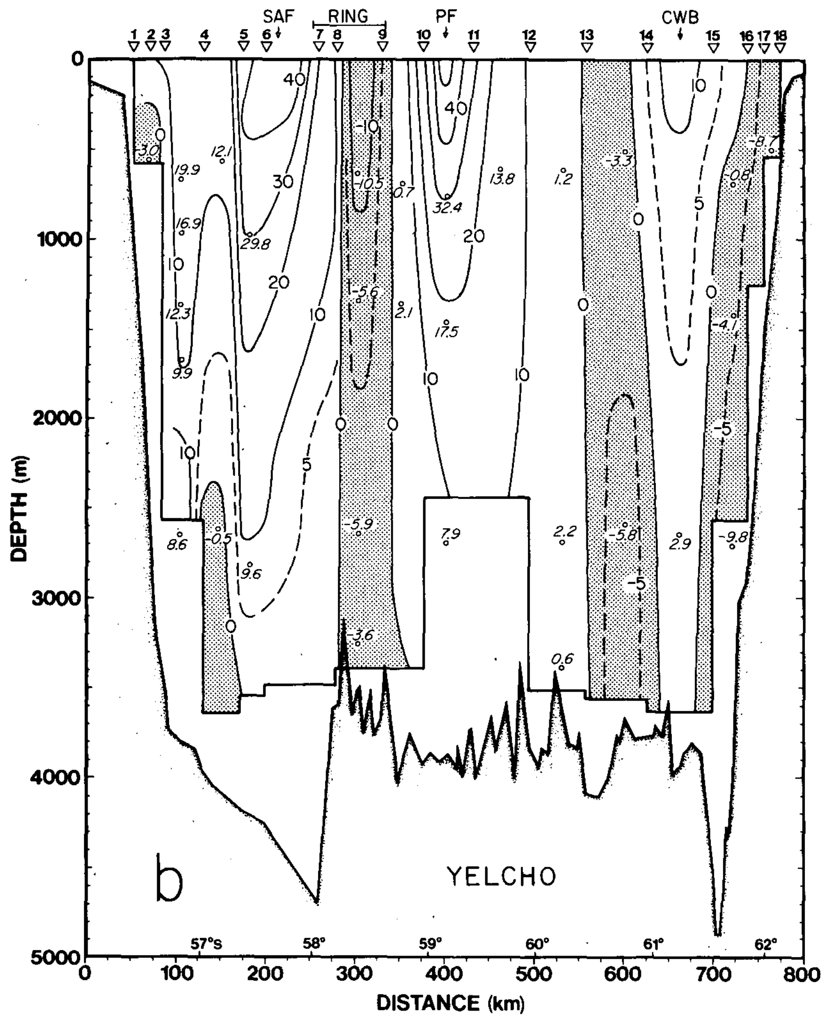

FIG. 4. (*Continued*)

Melville cruise. A 15-day average produces the best agreement for the *Yelcho* cruise and a 6 h average is best for the *Atlantis* II cruise. In a few cases, currents change so rapidly that shear agreement is poor except for one specific 6 h period between the times of the hydrographic stations.

NWP found the best agreement between measured speeds and geostrophic shears at averaging lengths longer than those found to be optimal in the present study. For four of their ten comparisons the agreement between shears is considerably better at the longest averaging period (3 weeks). The longer average was probably appropriate for the FDRAKE 75 data since only one of the five multiply instrumented moorings was in a front during both hydrographic surveys. Even this mooring, which had four current meters, is not directly comparable to the DRAKE 79 moorings, since the shallowest instrument was deeper than 2000 m. The smaller vertical shear at this depth reduces the disparity between measured and geostrophic speeds.

Two likely contributors to the disparity between measured and calculated shears are the effects of bottom topography and rapid lateral shifts in frontal positions. The combination of rapid frontal motions in an area of large bathymetric relief may result in a deep flow regime which is linked to the bottom topography and quite different from the flow in the upper layers. Such conditions are typical of the northern Drake Passage where the Subantarctic Front flows over a region replete with submarine mountains and ridges. An additional influence on the deep flow is a ridge south of Cape Horn (Fig. 1) which is only 50 km west of the northernmost moorings. Certain flow orientations may leave these moorings in the backwash of the ridge.

Fig. 2 shows comparisons of measured and observed shear in this northern passage region for several moorings and station pairs, including the *Melville* measurements at NT and ML1 which show particularly poor agreement. Dots show the directly measured component of velocity perpendicular to the sta-

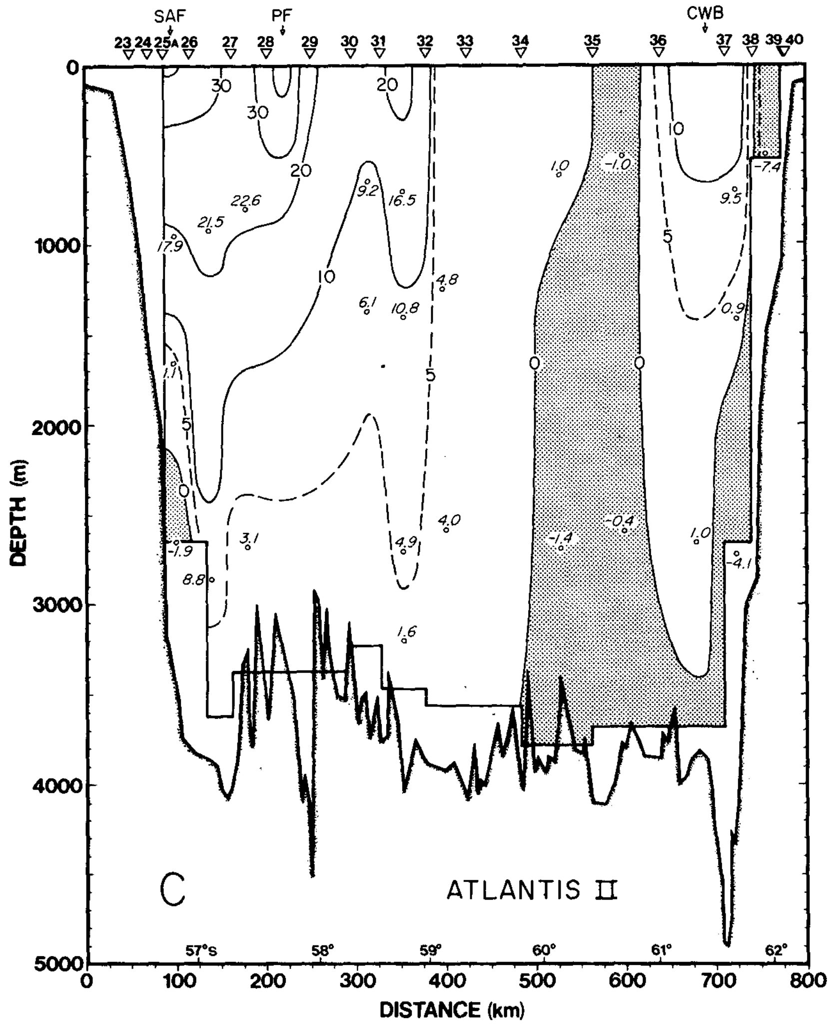

FIG. 4. (*Continued*)

tion pair averaged for different lengths of time. The continuous line is the relative speed calculated from density measurements at the station pair spanning the mooring. The relative shear curve has been offset to coincide roughly with the measured speeds at the optimum averaging period (shown in Table 2). The influence of a lateral shift of a narrow front is illustrated by data from mooring NT during the *Melville* hydrographic survey. The pair of stations was made on 26 January and shows high shears typical of the Subantarctic Front. The 1-day (26 January) average speeds at NT show very little shear, however. Because the NT mooring was nearly co-located with the northern hydrographic station, we infer that the Subantarctic Front was located south of NT at this time. Furthermore, for longer averaging periods at NT, recorded speeds were also low, showing that the front had been south of NT since the mooring was installed. A week later, however, the front wandered over the mooring and speeds increased. The measured velocity components (offset by a constant for display purposes) for a 6 h period on 3 February are shown as ×'s on Fig. 2. The shear agreement is quite good (range of $\Delta u = 6.3$ cm s^{-1}) and no doubt some further experimentation with averaging lengths could produce even better agreement. We feel that it is inappropriate, though, to reach into the future to match observed shears to the hydrographic data.

Both measured and calculated speeds are high at 1000 m near ML1. However, at the time of the hydrographic stations (1-day averages), the measured speed at the lower current meter (~1300 m above the bottom) was also quite large. Only for longer averaging periods, when the bottom current had reversed, are the shears in agreement. The variability in the speed at 2700 m is not present at the upper meter which recorded a nearly constant speed, emphasizing again the effects of bathymetry-current interactions on the deeper meters. Note that when speeds were high at both meters, measurements were made at greater depths as the mooring was blown over.

The remaining two curves in Fig. 2 show speeds at NT and ML2 during the *Yelcho* hydrographic survey when shear comparisons were more favorable. At NT speeds at the upper two meters are higher at longer averaging periods but lower at the deepest meter. At an averaging period of 15 days, the agreement between shears is quite good. Again, the variability at the bottom meter is not reflected in speeds at mid-depth. For ML2, which is located near the Subantarctic Front, the measured speeds are very steady and in good agreement with the relative shear.

The shear comparison in Fig. 2 shows only one component of speed and may misrepresent the current variability. XBT surveys on each DRAKE 79 cruise provided data that permit descriptions of the flow patterns in the upper layers. An XBT survey during the *Melville* cruise documented the formation and subsequent migration of a cold-core ring and is fully described by Peterson *et al.* (1982). Fig. 3 shows the temperature field at 150 m from a line of XBT's taken on 23–24 January 1979 when the ring was centered over ML2. The actual shape of the ring was determined in a subsequent XBT survey. Daily-averaged current vectors are shown for 21–26 January, the day the hydrographic section began. At ML1, the very high speeds at 700 m result from the flow at the northern edge of the ring, reinforced by the Subantarctic Front, whose influence extends north to NT. The upper instrument at ML2 malfunctioned during this period, but the deep current meter shows that higher speeds were present on 21 January, before the center of the ring passed over the mooring. The deep currents at NT and ML1 are erratic and appear to be in a different current regime from that of the upper meters, which show velocities in general agreement with the flow inferred from the isotherm pattern. NWP also found the poorest agreement between measured and geostrophic shears at the northern mooring for the FDRAKE 75 measurements. The decoupling of the deep flow is supported by record-length vertical cross-correlations of through-passage speeds between the shallowest (~600 m) and the deepest (~2600 m) instruments on NT and ML1. Fluctuations at these moorings are not significantly correlated (at zero lag) at the 90% level, whereas through-passage fluctuations at the remaining main-line moorings are correlated at the 95% level or higher. Where the fluctuations in the flow are not correlated with depth, a compromise is necessitated when attempting to match shears. This is illustrated on the right side of Fig. 3 which shows the current vectors for the optimum averaging period.

It should be noted that a good match between measured speeds and baroclinic shear does not guarantee that the best averaging period has been found or that the calculated reference speed is appropriate. Similar agreement might exist at another time or for another averaging period. An example can be seen in Table 2 for mooring ML1 during the *Yelcho* cruise. There are two averaging periods for which the range of Δu has minima: 1 day and 15 days. Although the speeds for both periods match the shape of the baroclinic shear profile well, the average speeds are lower for the 15-day average: the 1-day reference speed is -0.7 cm s^{-1} while the longer average gives -4.1 cm s^{-1}. The transports between the adjacent station pair using these two reference speeds would differ by 5.8 $\times 10^6$ m^3 s^{-1}.

Vertical sections of net geostrophic speed for the three DRAKE 79 cruises are shown in Figs. 4a–4c. Reference speeds for the optimum averaging length for each mooring have been used to reference the baroclinic speed, but the main features are not affected by the averaging period used. The heavy line near the bottom and sides of the passage shows the greatest common depths of the station pairs. The bathymetry shown is a composite representation based on that given by NWP and adjusted for soundings made on each of the cruises. The adjustments in the northern passage for the *Yelcho* cruise may be due to a slightly different cruise track or to erroneous soundings. For the missing moorings (ML3 and ML4) reference speeds were linearly interpolated between moorings ML2 and ML5. Reference speeds were also interpolated to adjust speeds between *Melville* stations 3 and 2, and between *Yelcho* stations 16 and 17, for which no direct measurements were available. Westward flow is shaded and the average speed for each current meter is shown. On all three sections the eastward flow at the Continental Water Boundary is bounded by westward flow to the north and south. The counterflow near the southern continental boundary, as measured by the two south-slope moorings, persists for nearly the entire year. These moorings, the southernmost deployed during the ISOS program, are the first which show a year-long westward flow—perhaps associated with the east wind drift near Antarctica. The westward velocity component north of the Continental Water Boundary is in the region where the ACC flows to the northwest before turning east through the Passage (Reid and Nowlin, 1971).

The strongest counterflows (between *Melville* stations 15 and 16 and *Yelcho* stations 8 and 9) are associated with rings. On the *Melville* section, the ring is centered on the line of hydrographic stations with the eastward flow of its northern flank adjacent to the Subantarctic Front. The *Yelcho* section shows the eastern edge of an approaching ring that crossed the main-line moorings after the hydrographic section.

The *Atlantis* II section shows a bimodal structure in the Polar Front similar to that observed during FDRAKE 75 by NWP. The main front is between stations 28 and 29, but an additional zone of high

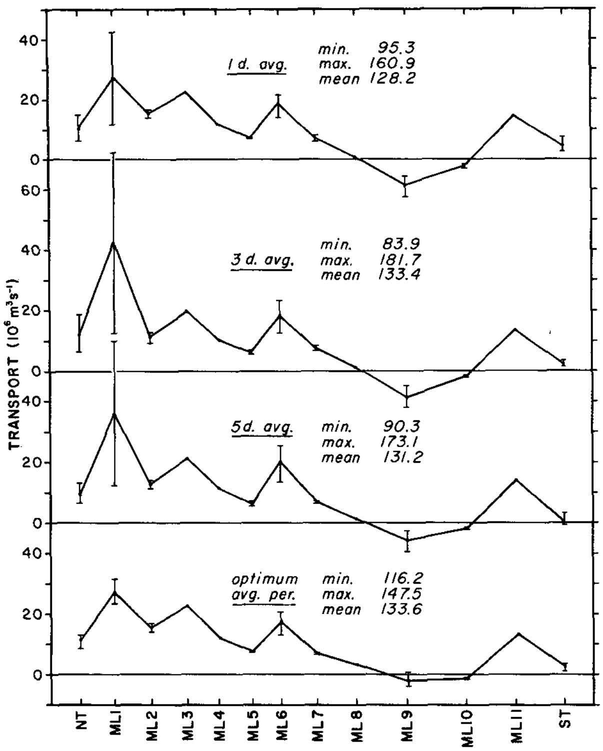

FIG. 5. Transport estimates between station pairs spanning the current meter moorings along the Main Line during the *Atlantis* II cruise. Transports are shown for direct current measurements averaged over 1-, 3- and 5-day periods and the optimum averaging period. The heavy line marks the average of the transports referenced to each current meter on moorings with more than one instrument. Bars show the minimum and maximum transports resulting from using different current meters to calculate the reference speed. The maximum, minimum and mean net transports (10^6 m^3 s^{-1}) for the entire secction are given for each averaging period.

speed occurs between stations 31 and 32 where the strong temperature minimum ($T < 0°C$) of the Antarctic Zone ends. The resulting velocity distribution shows a diffuse Polar Front, the northern edge of which was quite close to the Subantarctic Front. The Polar Front in the *Melville* and *Yelcho* sections by contrast is quite sharp with very similar speeds as a function of depth.

All three sections show westward flow at depth north of the Subantarctic Front. This flow is probably a local effect associated with the ridge which extends south from Cape Horn. The counterflow is especially strong on the *Melville* section below the intense westward surface flow.

4. Transport calculations

To compute the net transport between two hydrographic stations, the baroclinic transport is calculated relative to each current meter on a mooring spanned by the station pair, and a reference transport (current-meter speed times cross-sectional area) is then added to the relative transport. For each mooring there will be as many transport estimates as there are instruments on the moorings. For the various reasons discussed in the previous section different values for transport will result, depending on which current meter is used as a reference. As in NWP we have used all the current meters to reference transport and in addition have used several different averaging periods as well as the optimum averaging period for which measured speeds best match the baroclinic shears.

Fig. 5 illustrates the effect of different averaging periods on transport estimates between individual station pairs and on the total transport estimate for the *Atlantis* II cruise. The transports between station pairs spanning the moorings identified at the bottom of the figure are shown for directly measured currents averaged over 1-, 3- and 5-day periods as well as for the optimum averaging period. The heavy line connects the mean transport past each mooring and represents the average of the transports referenced to each current meter on the moorings. The mean transport may also be thought of as the baroclinic transport relative to 2500 db adjusted by the average offset between directly measured speeds and the geostrophic shear. For moorings with more than one current meter, the ranges of transports that result from using

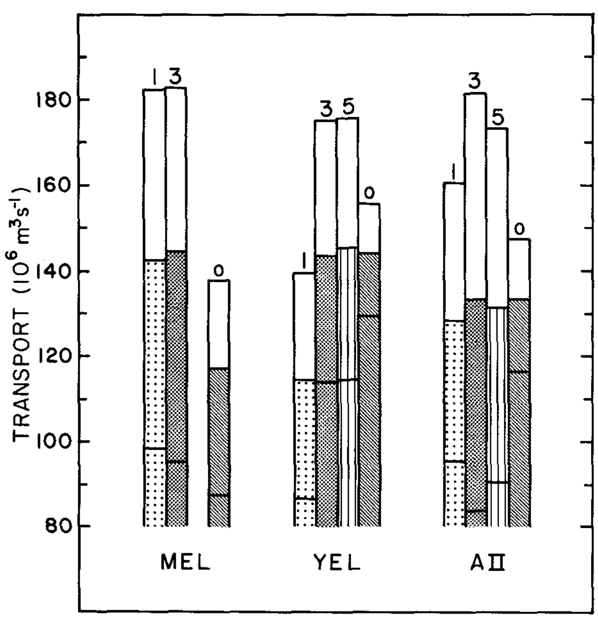

FIG. 6. Total transport estimates for the three hydrographic cruises during DRAKE 79. Net transports are shown for 1-, 3- and 5-day averages of direct measurements, and for the optimum averaging period (o). The shaded bar identifies the mean transport and horizontal lines above and below the mean give the maximum and minimum transports resulting from using different current meters to calculate the reference speed.

the largest and smallest reference speeds are shown. For moorings with no direct measurements (ML3, ML4 and ML8 for this cruise) reference speeds are linearly interpolated between adjacent moorings. Where only one direct measurement is available (ML11), an optimum averaging period cannot be determined, so it is estimated from adjacent moorings. For ML11 on the *Atlantis* II cruise the optimum averaging period is 3 days (see Table 2).

Several features of Fig. 5 are applicable to the *Melville* and *Yelcho* cruises as well. The largest ranges of transport (i.e., the poorest agreement between measured speeds and geostrophic shear) are found in the northern passage where the currents are most variable. Two other moorings which show relatively large ranges are ML6 and ML9 which have a Geodyne current meter positioned a few hundred meters above the bottom. Although the deep instruments are sometimes in harmony with the meters above, they sometimes have velocities which are anomalously low or in the opposite direction, suggesting bathymetric influence.

Fig. 6 presents the maximum, minimum and mean total transports for all three cruises as a function of averaging period. No estimate of transport at the 5-day averaging period is made for the *Melville* cruise since the hydrographic survey was made shortly after the mooring installation. For the *Melville* and *Atlantis* II cruises, almost the entire reduction in the range of transport at the optimum averaging period is due to a reduced range at one mooring—ML1. On the *Atlantis* II section, changes in the mean transport at ML1 are compensated by smaller changes at the remaining moorings so that the mean total transport remains nearly constant regardless of averaging period. On the *Melville* cruise, most of the reduction in the mean transport at the optimum averaging period is due to slower speeds at ML1. Low current speeds at ML8 for the 1-day averaging period account for most of the reduction in transport on the *Yelcho* cruise. The transports shown in Fig. 6 for the *Yelcho* section include an additional transport of 13.3×10^6 $m^3\ s^{-1}$ to extend the estimates between stations 10 and 12 (Fig. 4b) closer to the bottom. The extension was made by assuming that the deepest adjusted speed was constant to a depth of 3650 m, a depth comparable to the deepest common depth on the other two sections.

To estimate the probable errors in net transport on each cruise due to the mismatch between observed and calculated speeds, we calculate the average standard deviation of the transport estimates for the nine moorings (eight for the *Melville* section) with more than one instrument and apply this error to the remainder of the 15 main-line moorings (including missing moorings ML3 and ML4). The error estimate for the entire section is then the square root of the sum of the 15 transports variances at each mooring. Using these errors and the mean transport for the optimum averaging length, the net transports are:

Melville	$117 \pm 15 \times 10^6\ m^3\ s^{-1}$
Yelcho	$144 \pm 6 \times 10^6\ m^3\ s^{-1}$
Atlantis II	$137 \pm 10 \times 10^6\ m^3\ s^{-1}$.

Combined with the previous estimate by NWP,

FDRAKE 75 $124.0 \pm 15 \times 10^6\ m^3\ s^{-1}$,

the four net transports are remarkably close.

5. Discussion and conclusions

The most difficult problem in estimating net transport by combining data from current meters with those from hydrographic stations is reconciling direct measurements and baroclinic speeds. Even for closely spaced hydrographic data, there will always be a disparity between spatially averaged relative currents and direct measurements in a current regime with significant temporal and spatial variability. In Drake Passage, where narrow current cores are separated by broad regions of uniform properties and low speeds, the spatial variability is pronounced. The situation is further complicated by meanders and other lateral motions of the fronts. We have attempted to resolve the discrepency by averaging the direct measurements over that length of time which produces the best agreement between measured and baroclinic shears. The length of the average differs for each mooring depending on the local time and space scales. We had mixed success in matching shears; in many cases the agreement was quite good, but in several cases, no averaging period produced good agreement.

Vertical sections of net speed clearly show the high speeds associated with these fronts in Drake Passage. Cold core rings are present in two of the sections and the Polar Front in these two cases is narrow and intense. The *Atlantis* II section, without a ring, has a more diffuse Polar Front. All three sections show weak westward flow at the southern boundary of the Passage.

The average of the four ISOS net transport estimates is $130 \times 10^6\ m^3\ s^{-1}$. Two other studies have estimated the net transport through Drake Passage using a different method. Bryden and Pillsbury (1977) used weekly averaged speeds from six 35-week current records near 2700 m depth to estimate a mean barotropic (reference) transport of $39 \pm 36 \times 10^6\ m^3\ s^{-1}$. Fandry and Pillsbury (1979) used an objective analysis technique on the same data and calculated an average reference transport of $27 \pm 14 \times 10^6\ m^3\ s^{-1}$. Combining their estimates with the mean baroclinic transport relative to 2700 m (roughly 100×10^6 $m^3\ s^{-1}$) gave them net transport values of 139×10^6 and $127 \times 10^6\ m^3\ s^{-1}$.

The consistency of these six estimates suggests that not only is the relative transport through Drake Passage steady, but that the net transport may be far steadier than previously thought. The Bryden-and-Pillsbury and the Fandry-and-Pillsbury estimates, however, are based on the record-length mean reference transports relative to 2700 m. The 35 weekly average transports that constitute the mean have a large range—262×10^6 m^3 s^{-1} for Bryden and Pillsbury and 220×10^6 m^3 s^{-1} for Fandry and Pillsbury. Both studies note that much, or even all, of the apparent variability in transport may be due to errors in estimating the mean flow since mooring separations were considerably larger than the length scales of the velocity fluctuations. Further studies, based on the more densely sampled DRAKE 79 array data, may better describe the variability of ACC transport as a function of time during 1979.

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