# NOTES AND CORRESPONDENCE

## Volume Transport of the Antarctic Circumpolar Current from Bottom Pressure Measurements

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ABSTRACT

Measurements from bottom pressure gauges located at the north and south sides of Drake Passage are used to extend the one-year time series of volume transport of the Antarctic Circumpolar Current (ACC) given previously by Whitworth. A small error in that paper is corrected, and a revised transport time series is presented which shows the importance of including the transport in the northern and southern margins of Drake Passage. Direct measurements of vertical shear averaged across the passage, are in good agreement with geostrophic shear and suggest that the ACC is in geostrophic balance. Although most of the ACC transport is in the baroclinic field, transport fluctuations are mainly barotropic. Transport estimates based on pressure difference alone differ from the estimates of Whitworth by less than $10 \times 10^6$ m$^3$ s$^{-1}$. Fluctuations in transport of almost half of the mean value occur over periods as short as two weeks.

### 1. Introduction

A recent experiment conducted as part of the International Southern Ocean Studies (ISOS) demonstrated the feasibility of monitoring the transport of a major ocean current for an extended period of time. Data from the Dynamic Response and Kinematics Experiment, 1979 (DRAKE 79) were used to estimate the volume transport of the Antarctic Circumpolar Current (ACC) through Drake Passage for more than a year with errors estimated to be less than 10% (Whitworth, 1983). The monitoring experiment consisted of three separate hydrographic surveys, and the deployment of 17 current meter moorings and six precision pressure gauges.

The primary objective of this note is to extend the year-long transport time series at Drake Passage using the results of DRAKE 79 in conjunction with bottom pressure records at each side of the passage which began in 1977. We will demonstrate that a pair of pressure gauges can be used to estimate the transport with errors on the order of $10 \times 10^6$ m$^3$ s$^{-1}$ (10 Sv). During the course of this work, we discovered a small error in one of the time series reported by Whitworth (1983); the second objective of this note is to correct this error and also to provide an improved transport time series for 1979.

### 2. A modified net transport time series

The procedure used by Whitworth (1983) is illustrated schematically in Fig. 1 and is summarized herein. The time series of the relative transport in the lower shaded area was calculated using dynamic heights from two "transport" moorings (NT and ST) at each side of Drake Passage. The mean relative transport of the upper 500 m was estimated using dynamic heights from historical hydrographic data. A reference speed at 500 m was determined from a pair of pressure gauges (NP and SP) and was used to adjust the relative transports to obtain net transport. Because the across-passage distances at 500 and 2500 m are different, the spatially averaged speed at 500 m between the pressure gauges ($U_{500P}$, where $P$ denotes an average between the pressure gauges) is not a suitable reference speed with which to adjust the relative transport between 500 and 2500 m. Directly measured currents in the two slope regions were therefore removed from $U_{500P}$ to form $U_{500T}$, the spatially averaged speed at 500 m between the transport moorings.

The slope currents shown by Whitworth (1983, Fig. 3) are correct, but an error was made in removing the contribution of the slope regions from $U_{500P}$ to obtain $U_{500T}$. Correcting this error [which also alters the time series of net speed at 2500 m ($U_{2500T}$) and net transport] results in increased variability about a slightly larger mean value. The revised values are: $U_{500T}$, 11.96 ± 0.76 cm s$^{-1}$ (versus 11.84 ± 0.64 cm s$^{-1}$); $U_{2500T}$, 2.16 ± 0.83 cm s$^{-1}$ (versus 2.05 ± 0.69 cm s$^{-1}$); and the mean net transport, 123 ± 10.5 Sv (versus 121 ± 8.5 Sv).

Figure 2 shows plots of the corrected series $U_{500T}$, $U_{2500T}$ and net transport. The major differences between these series and the ones given by Whitworth (1983) are the increased magnitude of the high frequency fluctuations and small differences in the low-frequency signal. These departures are sufficient to

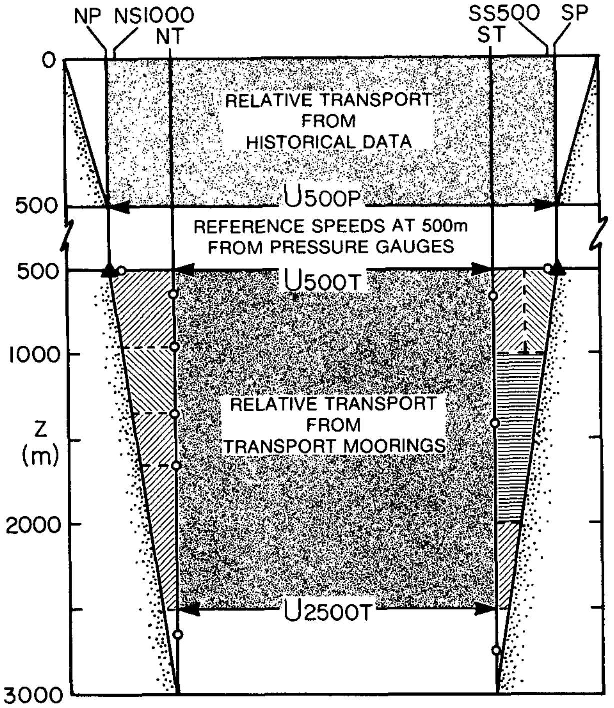

FIG. 1. Schematic cross section of Drake Passage illustrating the procedure used by Whitworth (1983) to calculate net transport (shaded area). Transport in the north and south slope regions (hatched areas) is estimated using direct measurements from current meters (open circles).

alter some of the coherence calculations discussed in that paper. It had been noted that $U_{500P}$ and $U_g$ (the baroclinic shear between 2500 and 500 m) were not coherent whereas $U_{500T}$ and $U_g$ were coherent for periods between 25 and 50 days (Whitworth, 1983, Fig. 5a). The corrected $U_{500T}$ is significantly coherent (at the 95% level) and in phase with $U_g$ only for periods between 10 and 13 days.

A lack of coherence between $U_g$ and $U_{500T}$ would imply that fluctuations in the speed at 500 m do not reflect fluctuations in the baroclinic shear between 2500 and 500 m. Yet, Pillsbury *et al.* (1979) presented data from three depths at a mooring in the central passage that showed excellent correspondence between current speed and vertical shear. Peterson (1985) analyzed the geostrophic shear between station pairs in the northern, central and southern passage, and found strong relationships between speeds at middepth (between 400 and 1000 m) and surface speeds. Although $U_{500T}$ and $U_g$ may not be statistically coherent, Fig. 2 shows that there are periods when fluctuations in both time series are in phase (e.g., February–March, October–November). We suspect that the across-passage averages of $U_g$ and $U_{500T}$ would be better related if the eddy-rich northern passage with its complicated bathymetry were not included. It is here that the relationships of Peterson (1985) showed the greatest scatter, and where measured and geostrophic shear showed the poorest agreement (Nowlin *et al.,* 1977; Whitworth *et al.,* 1982).

Whitworth (1983) noted the relationship between fluctuations in current speed in the slope regions and lateral shifts of the northernmost (Subantarctic Front) and southernmost (Continental Water Boundary) fronts in Drake Passage. The transport above 500 m in the slope regions was included in the net transport estimate since $U_{500P}$ was used as a reference speed. Not included, however, was the triangular region below 500 m between the transport moorings and the pressure gauges (see Fig. 1). It is possible to estimate the transport in these regions by extrapolating the direct measurements at NT and ST to the northern and southern continental slopes. The through-passage components of speed (toward 062°T) from moorings NT and NS1000 were applied to the appropriate cross-sectional areas as shown in Fig. 1 to yield daily estimates of transport in the north slope region. In the 45 km wide south slope region, the flow at mooring ST at 700 m was toward the east whereas that near SP was toward the west. Half the area between ST and SP from 500 to 1000 m was apportioned to each flow regime. At 1400 m on ST, the flow alternated between easterly and westerly, and the through-passage component of speed was applied to the area between 1000 and 2000 m. The westerly flow recorded at 2700 m on ST was applied to the

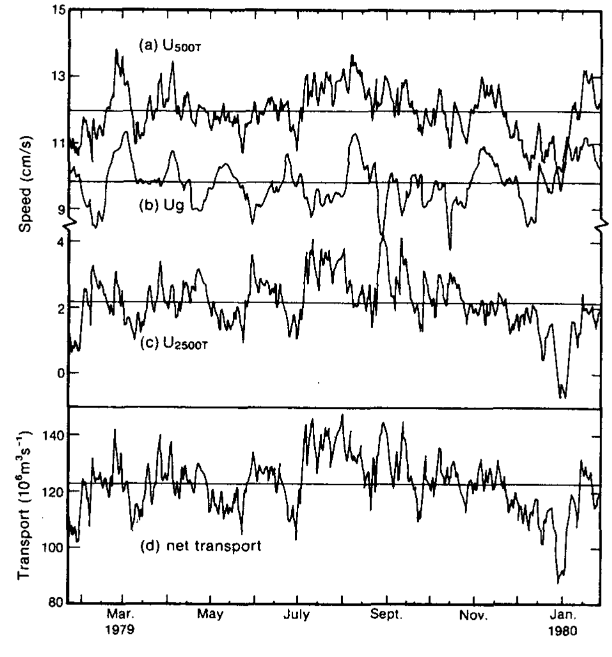

FIG. 2. Through-passage (towards 062°T) speeds averaged between NT and ST at (a) 500 m and (c) 2500 m and (b) the across-passage averaged shear between 2500 and 500 m. The net transport through Drake Passage from January 1979 to February 1980 (d). The time series a, c and d are corrected versions of those presented in Whitworth (1983) Figs. 4a, d and Fig. 7.

area between 2000 and 2500 m. It was originally felt that such extrapolation in an active boundary region would be risky and might degrade the net transport estimate rather than enhance it. The analysis which follows leads us to believe that inclusion of the slope transport below 500 m improves the net transport time series.

Figure 3 shows time series of the slope region transport below 500 m and a modified net transport time series which includes this contribution. Although in the mean the slope regions transport only 2 Sv, there are times when their contribution exceeds 15 Sv. Inclusion of the slope transport below 500 m reduces the variability of the net transport estimate. Our current estimate of net transport has a mean of 124.7 Sv and a standard deviation of 9.9 Sv. The coherence between the transport below 500 m in the slope regions and the baroclinic transport between 2500 and 500 m relative to 2500 m (not shown) is significantly (95%) different from zero for periods between 17 and 26 days, and 180° out of phase. This relationship demonstrates the effect of a front moving into the slope region as suggested by Whitworth (1983). For instance, if the Subantarctic Front (SAF) shifts northward past NT, the relative transport averaged between the transport moorings will decrease while the transport in the north slope region increases. The effect of the slope transport on the modified net transport time series can best be seen in the last two months of the records (Fig. 2c and Figs. 3a, b). Unless otherwise stated, all subsequent discussion is based on our improved series of net transport which includes the transport in the slope regions.

## 3. A geostrophic comparison

Can it be shown that the ACC is in geostrophic balance? For pairs of hydrographic stations spanning current meter moorings, geostrophic shear can be made to agree with measured shear if the direct measurements are averaged over an appropriate period (Nowlin *et al.*, 1977; Whitworth *et al.*, 1982). To our knowledge, a geostrophic comparison has never been attempted for long-term measurements of geostrophic shear and currents. The north and south transport moorings provided daily estimates of dynamic height between 500 and 2500 m from which the shear ($U_g$) was calculated. Direct current measurements were also available at 500 and 2500 m on the line of moorings between NT and ST. But, because of the design of the DRAKE 79 experiment and some data loss, a rigorous geostrophic comparison (such as that by Horton and Sturges, 1979, for the MODE data) cannot be made. Mooring separations were designed to be at the horizontal de-correlation length scale (Sciremammano *et al.*, 1980) so that velocity estimates at adjacent moorings would be independent. Also, two adjacent moorings in the northern passage (ML3 and ML4) were not recovered, resulting in a 125 km gap in the current measurements at 500 and 2500 m; instrument failure at a central passage mooring (ML8) resulted in a second 125 km gap at 2500 m (Whitworth, 1983).

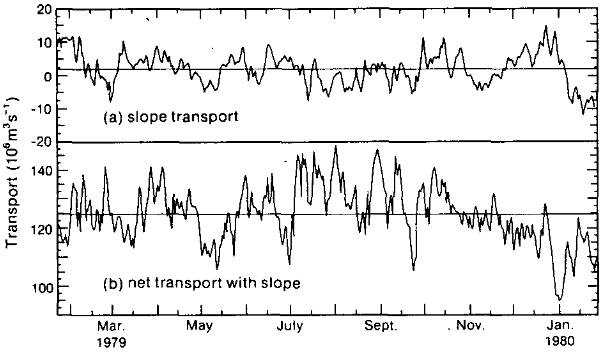

FIG. 3. (a) Transport in the north and south slope regions between 500 and 2500 m. (b) Net transport through Drake Passage from January 1979 to February 1980 including the transport in the slope regions. This time series is the sum of those in Figs. 2d and 3a.

Daily estimates of the across-passage average of the through-passage velocity components at 500 and 2500 m were made by linear interpolation of direct measurements. Time series of the directly-measured shear and geostrophic shear are shown in Fig. 4. For display purposes, both series have been smoothed with a 10-day low-pass filter. As noted by Whitworth (1983), the direct estimates of speed at 500 m are poor in comparison with the speed determined from pressure measurements. When a front is in the gap between ML2 and ML5, the spatially averaged current will be underestimated. Intervals during which either Polar or Subantarctic fronts are between ML2 and ML5 (Nowlin *et al.*, 1985, Fig. 8) are shaded in Fig. 4. We would expect the directly measured shear to be underestimated during these periods. For times immediately before or after the shaded periods, a front is near ML2 or ML5 and the direct measurements are likely overestimated.

In spite of the sampling problems, the fluctuations in the two series are generally in phase although the magnitudes differ. The two estimates of shear are coherent (at the 95% level) and in phase for periods between 26 and 49 days. The results suggest that fluctuations in the ACC are in rough geostrophic balance.

## 4. An extended transport time series

To what extent can the net transport of the ACC through Drake Passage be monitored with pressure gauges alone? Figure 5 shows the coherence and phase of the net transport time series from Section 2 and the north–south pressure difference ($P_N - P_S$) at 500 m. The two series are coherent and in phase at

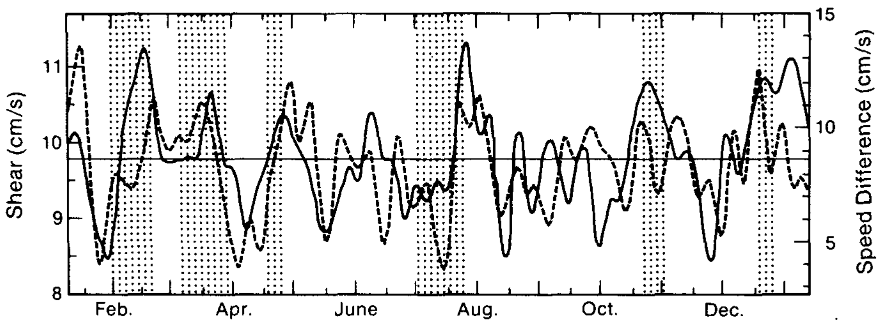

FIG. 4. Geostrophic shear between 2500 and 500 m from the transport moorings (solid line) and the through-passage component of velocity difference between 500 and 2500 m estimated from spatial averages of direct current measurements (dashed line). Both series have been smoothed with a low-pass filter having a half-amplitude point of ten days. Note that the two speed scales are different. Shading shows periods when direct speed measurements are expected to provide poor estimates of shear since fronts were located near inoperative current meters.

virtually all frequencies. Of course, some coherence is expected since the reference speeds $U_{500P}$ and $U_{500T}$ are derived from the pressure difference and figure prominently in the net transport calculation; but a major component of net transport, that associated with the shear between 2500 and 500 m, is not well represented by the pressure difference.

The baroclinic transport above and relative to 2500 m accounts for about 70% of the net transport through Drake Passage (Whitworth, 1983), and about half of this is between 2500 and 500 m. Thus, roughly 35% of the net transport is in the baroclinic field below 500 m, fluctuations in which are generally not reflected in pressure difference (since $U_{500P}$ and $U_g$ are not coherent). But the standard deviation of the relative transport between 2500 and 500 m (5.3 Sv) is only about one-half that of net transport (9.9 Sv). Therefore, although most of the transport of the ACC is in the baroclinic field, the relative transport is not the primary source of variability in net transport. Wearn and Baker (1980) noted that if the speed fluctuations at 500 m (range of 3.3 cm $s^{-1}$ for 1977–78) corresponded to barotropic fluctuations in the ACC, the total transport would vary by about 65% of the mean value; if transport fluctuations were baroclinic (and scaled in depth with the mean velocity profile) their range would be about 25% of the mean. In 1979, the range of the pressure difference corresponds to a range in speed of 2.4 cm $s^{-1}$ averaged across Drake Passage at 500 m. If the speed fluctuations were barotropic, they would represent a transport range of 59 Sv. The actual range of estimated transport for 1979 is 54 Sv. Thus, a large part of the transport variability appears to be in the barotropic field, and pressure difference should provide a good estimate of net transport.

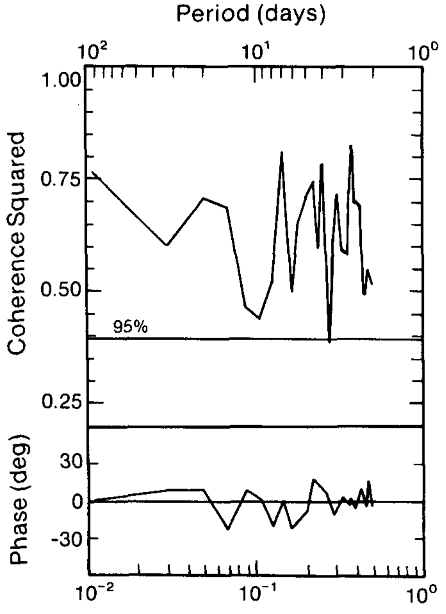

FIG. 5. Coherence and phase between net transport (Fig. 3b) and pressure difference at 500 m. Each point represents the average of seven spectral estimates within the band $f \pm 9.46 \times 10^{-3}$ cycles per day.

Forty-hour low-passed time series of transport [in units of $10^6$ $m^3$ $s^{-1}$ (1 Sv)] and $U_{500P}$ (in cm $s^{-1}$) for 1979 were used as input to a linear regression model to give a time series of estimated transport ($T'$) of the form

$$T' = AU_{500P} + B$$

where $A$ and $B$ are constants. In the first model, $U_{500P}$ was fit to the net transport without the contribution of the slope regions below 500 m. The correlation coefficient for this model is 0.69, and it accounts for 48% of the variance in the transport time series. The constants $A$ (17.2) and $B$ (−65.8) correspond to the across-passage area above 2500 m ($17.5 \times 10^8$ $m^2$)

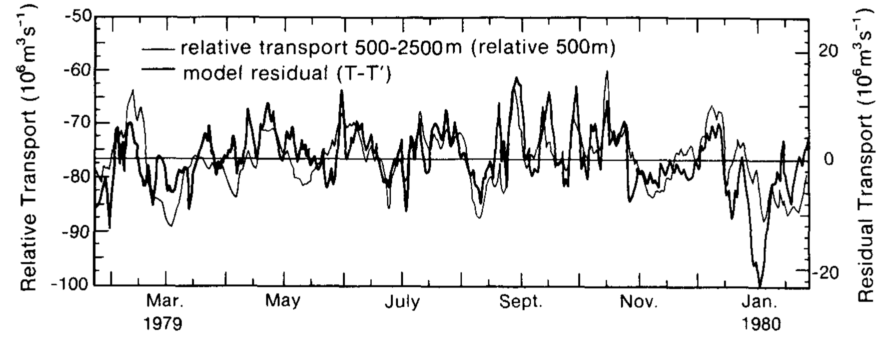

FIG. 6. The error in the linear regression model of net transport compared to the relative transport below and relative to 500 m. Much of the error is accounted for by the ommission of the relative transport in the model.

and the baroclinic transport between 0 and 2500 m relative to 500 m (−70.3 Sv).

The second model fit $U_{500P}$ to the net transport including the transport in the slope regions below 500 m ($T' = 18.7U_{500P} - 81.0$). The correlation coefficient for this model is 0.80, and it explains 65% of the variance in net transport. Including the variability in the slope regions results in considerable improvement in predicting transport from pressure difference.

The difference between net transport ($T$) and the modeled transport ($T'$) can be explained in large part by the model's inability to incorporate fluctuations in the relative baroclinic transport below 500 m. Figure 6 shows time series of the model residual ($T' - T$) and the relative baroclinic transport between 500 and 2500 m (relative to 500 m). Periods when the transport below and relative to 500 m is strongly westward (more negative) correspond to periods of reduced net transport. During such periods, the model tends to overestimate the transport since the pressure difference does not supply information on the shear below 500 m. The residual series has a range of 39 Sv and a standard deviation of 5.9 Sv. It is coherent with the baroclinic transport below and relative to 500 m which has a range of 29 Sv and a standard deviation of 5.3 Sv. The largest difference between the model and the net transport is 24 Sv but more than 90% of the model estimates are in error by less than 10 Sv (1.7 standard deviations).

The 1979 pressure data add a third year to the data presented by Wearn and Baker (1980). End-point matching of the two data sets results in a continuous three-year time series of pressure difference. The 1979 data have been calibrated by using hydrographic data and direct current measurements to derive speed from pressure difference (Whitworth, 1983). This calibration can be extended to the previous years to provide a three-year time series of speed. The linear regression coefficients relating transport and pressure difference for 1979 can then be applied to the three-year pressure-difference record to give an extended estimate of transport through Drake Passage. It should be noted that this procedure merely rescales the pressure-difference time series.

In principle, the tedious process of calibrating pressure gauges could be avoided in subsequent monitoring experiments if the three-year pressure-difference time series is representative of the long-term mean. Table 1 shows the average 500 m speeds and standard deviations for the entire three-year record and for three one-year segments of that record. Also shown is the standard deviation from a pair of pressure gauges recovered in 1982. The continuity of the pressure difference record was broken in year 4 (1980–81) when the northern pressure gauge could not be recovered (Wearn, 1981). The means from segments of the three-year continuous record appear to be relatively steady: if speed fluctuations were barotropic, the standard deviation about the three-year mean speed would correspond to transport fluctuations of 9.8 Sv; the difference of 0.3 cm s$^{-1}$ between year 1 and year 2, if barotropic, would correspond to a difference in transport of only 5.3 Sv. The standard deviations illustrate that speeds during years 2 and 5 were considerably more variable than during years 1 and 3.

For the extended transport time series, the average

TABLE 1. Statistics for the 500 m speed across Drake Passage as determined from pressure difference data.

| | Speed (cm s$^{-1}$) | |
|---|---|---|
| Year | Mean | Standard deviation |
| 1 (1/22/77–1/22/78) | 10.68 | 0.45 |
| 2 (1/23/78–1/22/79) | 10.98 | 0.70 |
| 3 (1/23/79–2/20/80) | 10.93 | 0.45 |
| three-year period | 10.87 | 0.56 |
| 5 (3/23/81–3/10/82) | — | 0.70 |

pressure difference from year 5 was set equal to the mean from the first three years, and the coefficients from the linear regression model were applied to the 40-hour low-pass time series of speed. The resulting transport time series were smoothed with a 10-day low-pass filter for display purposes and are shown in Fig. 7. During the first three years, the modeled transport ranges from 98 to 154 Sv and has a standard deviation of 10.3 Sv, or 8% of the mean value of 123 Sv. The modeled transport during 1981–82 ranges between 95 and 158 Sv with a standard deviation of 12.6 Sv. The first three years give the impression that transport builds up to a maximum over relatively short intervals (two months) and then diminishes slowly over longer intervals (six months). In June 1981, however, the transport decreased 56 Sv in less than a month. This is comparable to the 46 Sv transport increase during two weeks in August 1978. The larger fluctuation represents a change of 46% of the mean transport.

There is some suggestion of a seasonal signal in transport as shown by the inset in Fig. 7, but the interannual differences are large. Except for 1979, there is a relative maximum in transport in October. A relative minimum occurs in July except for 1979 which has a maximum. Only during 1981–82 is there a clear seasonal signal with maxima in May and October and minima in July and January. This is nearly opposite the phase noted by van Loon (1972) for the north–south sea level difference, but it is in good agreement with his north–south atmospheric pressure difference. It is clear from Fig. 7 that seasonal fluctuations are not phase-locked. It is ironic that the year for which the best transport estimate exists (1979) is significantly different from the other three years.

## 5. Conclusions

We have shown that a small but significant portion of the ACC transport occurs in the narrow slope regions at the northern and southern margins of Drake Passage. Although the mean slope transport during 1979 was almost zero, the occasional presence of fronts there affects the variability of the net transport. A new year-long net transport time series which includes the contribution of the slope regions is less variable than one which neglects these areas.

We have compared continuous measurements of geostrophic shear with direct current measurements at 500 and 2500 m for one year. Although the current meter moorings were relatively far apart and there were several instrument failures, the two measures of shear are in general agreement. It is likely that better measurements would show the ACC to be in geostrophic balance.

Taking advantage of the fact that net transport is highly correlated with the across-passage pressure difference at 500 m, we have constructed a linear regression model that permits us to extend the net transport time series. Although there is some evidence of a seasonal signal in transport, interannual differences exist for the four years during which transport was modeled. On two occasions, transport fluctuations approaching 50% of the mean transport occurred over intervals of less than a month.

Although this paper has focused on the transport at Drake Passage, recent evidence suggests that the results may apply to the ACC as a whole. Fu and Chelton (1984) have used sea level measurements derived from the Seasat altimeter to document an increase in sea surface slope near Drake Passage which corresponds to the July 1978 bottom pressure

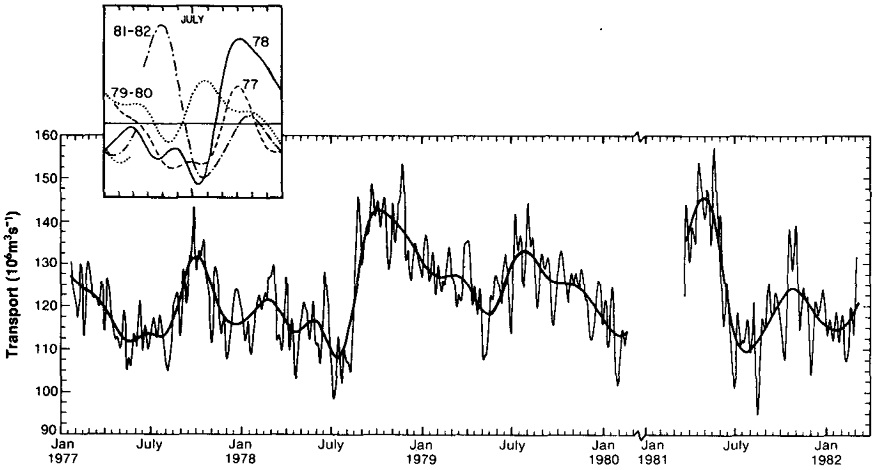

FIG. 7. Linear regression model of the net transport through Drake Passage from January 1977 to February 1980 and from March 1981 to March 1982. The light line shows 10-day low-pass filtered transport which is smoothed with a 90-day low-pass filter to illustrate the low-frequency variability. The inset shows year-long segments of the 90-day low-passed series.

signal. Measurements from six locations show that the changes in sea level across the ACC are zonally coherent.

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