Variability of Deep Flow in the Drake Passage from Year-Long Current Measurements

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ABSTRACT

To investigate the reasons for the wide variation in previous estimates of transport of the Antarctic Circumpolar Current through the Drake Passage, an analysis of the spatial and temporal variability of currents at 2700 m depth is made from year-long current measurements on six moorings in the Drake Passage. The currents are found to vary over time scales of about two weeks and over spatial scales shorter than 80 km. An average of the six down-channel velocity components is used to estimate the spatially averaged down-channel velocity, or mean flow, at 2700 m. This mean flow varies from 7.6 to -2.9 cm s^{-1} and has a root-mean-square (rms) amplitude of 2.0 cm s^{-1} about its time-averaged value. Provided the geostrophic transport relative to 2700 m depth remains constant in time, these variations may be interpreted as temporal variations of 260×10^6 m^3 s^{-1} in total transport with an rms amplitude of 50×10^6 m^3 s^{-1}. The wide variation in previous estimates of transport from short-term measurements can be understood in terms of this observed variation in mean flow. The time-averaged mean flow at 2700 m depth is estimated to be 1.56 ± 1.44 cm s^{-1} which implies that a transport of $39\pm36\times10^6$ m^3 s^{-1} should be added to the geostrophic transport of about 100×10^6 m^3 s^{-1} relative to 2700 m to obtain an estimate of the time-averaged total transport through the Drake Passage.

1. Introduction

Because models of the Antarctic Circumpolar Current are usually assessed in terms of their accuracy in predicting the transport through the Drake Passage (Munk and Palmén, 1951; Fofonoff, 1955; Gill and Bryan, 1971), it is important to have an accurate estimate of the transport. For a long time there has been a controversy concerning the magnitude of the transport through the Drake Passage (Gordon, 1967; Reid and Nowlin, 1971; Foster, 1972). This controversy makes it impossible to discriminate between various models which differ in predicted transport by hundreds of sverdrups[2] and to isolate the dominant dynamical balances in the circumpolar regions.

Before direct current measurements were made in the Drake Passage, the transport controversy centered on the choice of the level of no motion, or equivalent, used for referencing geostrophic calculations. Gordon (1967) summarized previous estimates of total transport from four hydrographic sections across the Drake Passage. These estimates varied from zero to 218 sverdrups depending on the method used to reference the geostrophic velocities. Reid and Nowlin (1971) noted that the geostrophic transport relative to a fixed reference level was nearly constant for all four hydrographic sections so that the differences in estimates of total transport were due to differences in reference surfaces.

Surprisingly, the controversy persisted after three sets of direct current measurements were made to estimate reference level velocities. Based on 5 days of current measurements, Reid and Nowlin (1971) estimated a total eastward transport of 237 sverdrups. Based on 13 days of current measurements, Foster (1972) made several estimates of total transport ranging from 72 sverdrups eastward to 62 sverdrups westward. Foster found that the geostrophic velocities were most consistent with measured velocities if he chose a level of no motion which varied in depth across the Passage. The estimate of total transport with this variable reference level was 5 sverdrups westward. Using current measurements on 12 moorings during a three-week period, Nowlin *et al.* (1977) made a third estimate of total transport of 124 sverdrups. Nowlin *et al.* (1977) also confirmed that all hydrographic sections including that of Foster (1972) yield nearly the same geostrophic transport relative to 3000 db. Thus, the differences in measured velocities used to reference the hydrographic sections cause the differences in total transport observed by Reid and Nowlin (1971), Foster (1972) and Nowlin *et al.* (1977).

To determine whether the differences in previously reported velocities and hence in previous estimates of total transport are due to the temporal or spatial variability of the currents, current records from an array of six current meters deployed for one year

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[2] One sverdrup = 1×10^6 m^3 s^{-1}.

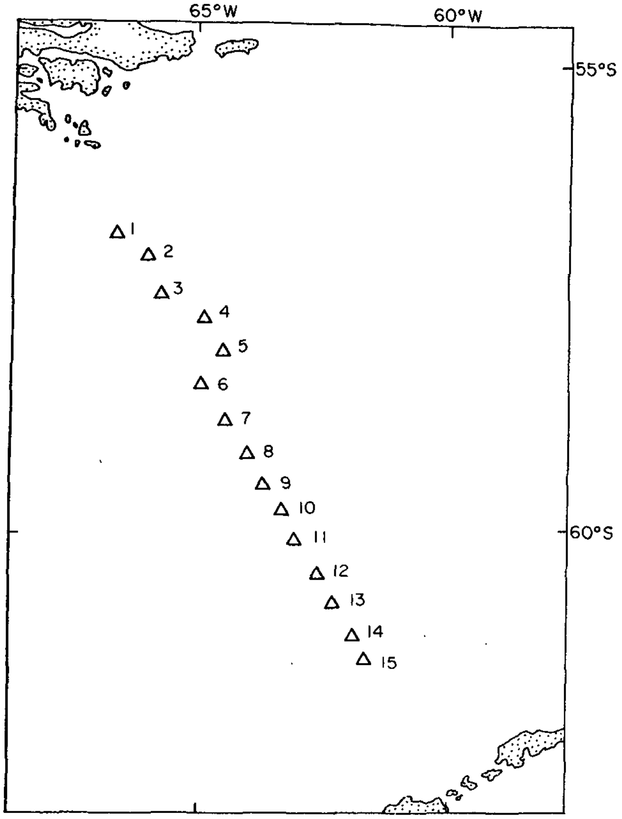

FIG. 1. Positions of the 15 moorings deployed in the Drake Passage during February and March 1975.

at 2700 m depth in the Drake Passage are analyzed. The error in spatially averaged down-channel velocity, to be called mean flow, due to the spatial variability of the measured currents is estimated. In addition, the temporal variability of the mean flow and its relation to variability in total transport is investigated. Finally, a time-averaged mean flow and its error due to temporal and spatial variability are estimated in order to provide a mean down-channel velocity at 2700 m to which hydrographic sections can be referenced.

2. Data and methods

As part of the International Southern Ocean Studies (ISOS) FDRAKE field program, an array of 43 current meters on 15 moorings was deployed across the Drake Passage during February 1975 (Figs. 1 and 2). Seven of the moorings were recovered after three weeks. Of the remaining eight moorings, seven were recovered intact in February 1976. Only the single current meter on mooring 5 was lost due to the ship cutting the mooring line in two places. One objective of this array was to measure currents at 2700 m depth on each mooring so that geostrophic velocities from hydrographic sections could be referenced to a common depth. The common depth was chosen to be 2700 m to ensure mooring survival in this region of energetic currents. Emphasis in this paper is placed on estimating the spatially averaged velocity at 2700 m depth from the six long-term current records closest to 2700 m depth (Fig. 3). Nowlin *et al.* (1977) have used the measured currents during the initial three-week period to reference geostrophic velocities obtained from hydrographic sections. Descriptions of results from the entire array will be published separately.

To eliminate higher frequency inertial and tidal motions, the eastward and northward velocities from each of the current meters are put through a low-pass filter with half-power at a period of 40 h (Mooers *et al.*, 1968) and averaged to daily values. The daily velocities are then rotated to yield velocity components perpendicular (62°T, called down-channel velocity) and parallel (332°T, called cross-channel velocity) to the line of moorings. Because only down-channel velocities are used to reference hydrographic sections across the Drake Passage, the following analysis concentrates on the down-channel component of velocity.

The objective of this paper is to estimate the spatially averaged down-channel velocity, called mean flow, at 2700 m and examine its contribution to estimates of total transport through the Drake Passage. This mean flow is calculated by averaging daily down-channel velocities for the six long-term current records (Fig. 4a), since the current meters were distributed nearly equally across the Passage. Since the vertical gradients of geostrophic velocity are small near 2700 m (Nowlin *et al.*, 1977), the velocities are not corrected for their variation from the mean depth. To estimate statistically the errors in this mean flow, it is necessary to determine the temporal and spatial scales over which the current fluctuations at 2700 m are independent. These scales of independence can be considered to be estimates of the shortest separations over which the currents become uncorrelated.

To estimate the temporal scale of independence, an autocorrelation function is calculated for each time series of down-channel velocity. Following Davis (1976), the length of time required for an independent velocity measurement is estimated to be

$$\sum_{\tau=-n\Delta t}^{\tau=+n\Delta t} C^2(\tau)\Delta t,$$

where $n\Delta t$ is the greatest lag τ for which the autocorrelation $C(\tau)$ is significantly different from zero at the 95% confidence level. This period of independence for down-channel velocities varies from 4.9 to 9.9 days and averages 6.9 days for the six records. For the mean flow, the period of independence is 6.8 days (Table 1). The first zero-crossing of the autocorrelation function for each record is used to

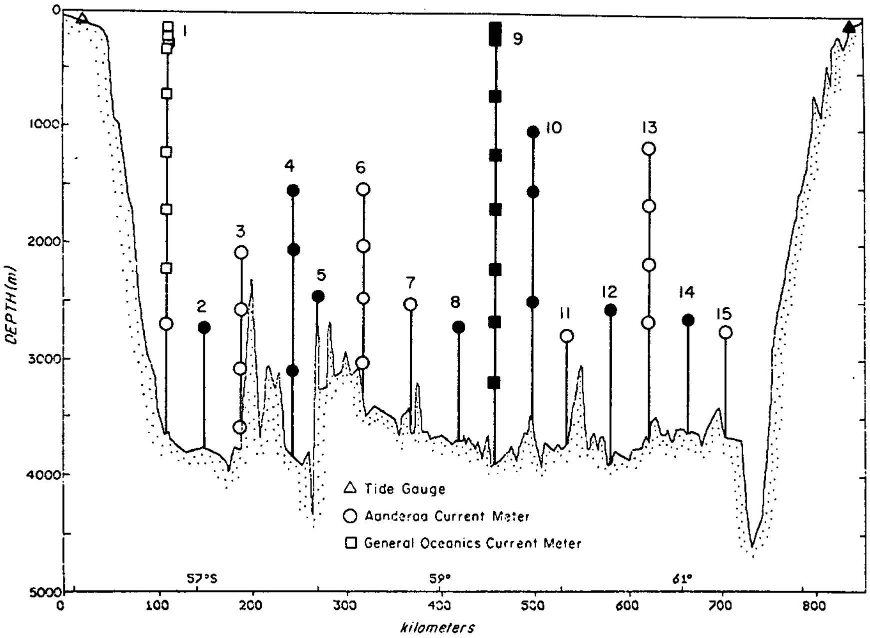

FIG. 2. Array of 43 current meters on 15 moorings deployed in the Drake Passage in February and March 1975. Moorings with short-term current meters (open symbols) were recovered after three weeks. Moorings with long-term current meters (solid symbols) were left in the Passage for a period of one year.

estimate the typical time scale of the dominant velocity fluctuations. This time scale varies from 6 to 32 days and averages 14 days for the six records. The typical time scale for the mean flow is 15 days (Table 1).

To determine whether the current fluctuations measured on the six moorings at 2700 m depth are spatially independent, cross-correlation coefficients between each pair of down-channel velocity time series are calculated. Only the cross correlation for velocities on moorings 10 and 12, separated horizontally by 78 km, is significantly different from zero at the 95% confidence level. The cross correlation for 10 and 12, however, is negative and the coherence between

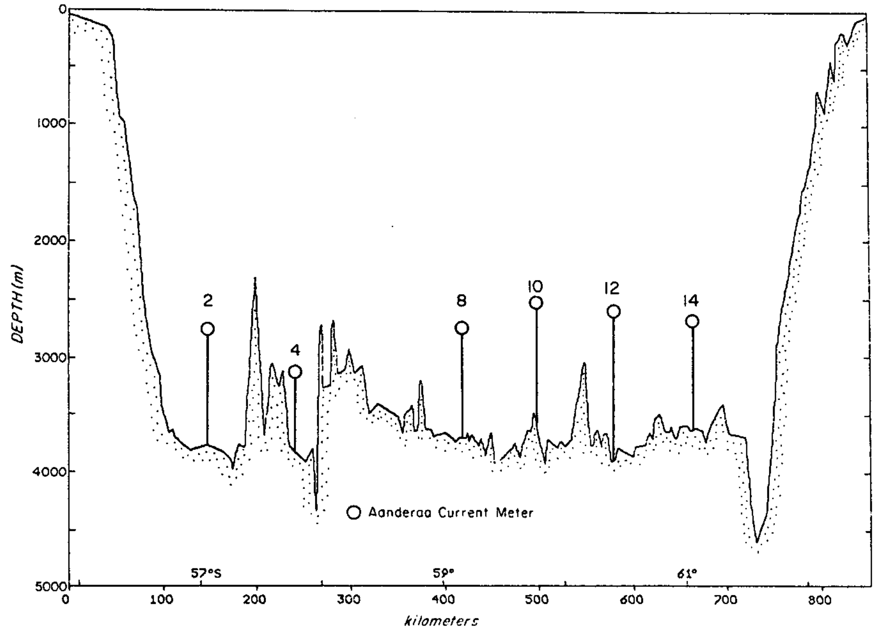

FIG. 3. Long-term current meters used in this analysis of mean flow at 2700 m.

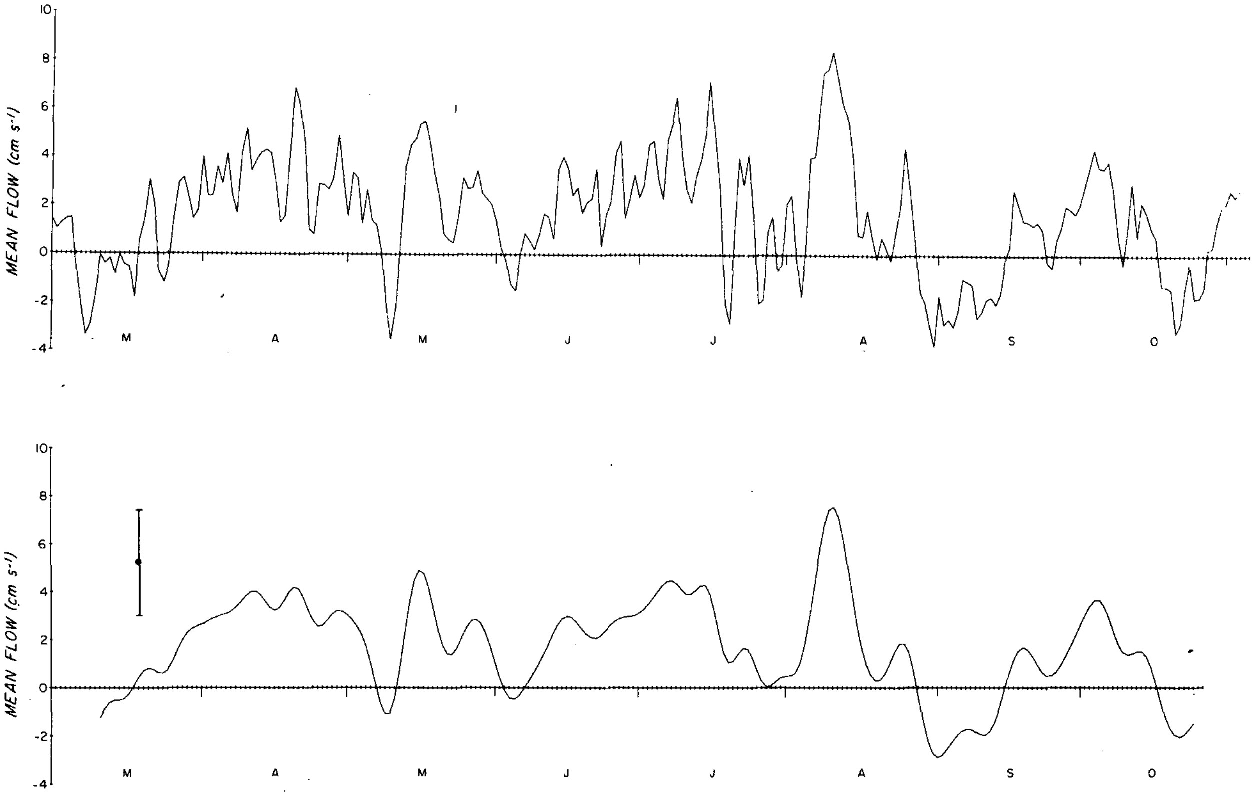

FIG. 4. Mean flow at 2700 m depth, defined as the spatial average of the down-channel velocities from the six current meters: (a) daily values of mean flow versus time; (b) mean flow filtered with a low-pass filter with bandwidth equal to 6.3 days. The rms amplitude of the mean flow, determined from the bottom record, about its time-averaged value is 2.0 cm s^{-1}.

down-channel velocities on 10 and 12 indicates significant coherence in several frequency bands where the phase difference is approximately 180°. Cross-correlation coefficients for other mooring pairs separated by about 80 km (moorings 8 and 10, 12 and 14) are not significant. To be certain that the very low frequency motions are not correlated, the down-channel velocities are put through an additional low-pass filter with half-power at 12.5 days and the cross correlation coefficients recalculated. Again, only the cross correlation for velocities on moorings 10 and 12 is significant but negative. Thus, the down-channel velocity fluctuations vary over spatial scales shorter than 80 km so that the spatial scale of independence at 2700 m is less than 80 km and the fluctuations are independent at each mooring.

TABLE 1. Depth and length of current records used to estimate mean flow at 2700 m depth. The mean flow is an average of the six currents. The time scale of independence is determined from the variance of the autocorrelation function for down-channel (62°T) velocity. The typical time scale of variability is determined by the period of the first zero-crossing of the autocorrelation function.

Mooring	Depth (m)	Length of current record (days)	Time scale of independence (days)	Typical time scale (days)
2	2770	291	6.4	16.5
4	3100	342	4.9	9.5
8	2750	351	8.5	32.0
10	2520	352	5.6	6.0
12	2600	254	6.2	6.0
14	2670	332	9.9	11.5
Mean flow	2730	250	6.8	15

Thus, the current fluctuations are independent approximately every 7 days at each mooring. Seven-day averages of down-channel velocity at each mooring are estimated and their average for each 7-day period is used to estimate weekly mean flow at 2700 m (Table 2). In addition, the daily time series of mean flow is put through a low-pass filter of bandwidth equal to 6.3 days to yield a time series of mean flow which has independent values approximately every 7 days (Fig. 4b). This time series has a root-mean-square (rms) amplitude about its time-averaged value of 2.0 cm s^{-1}.

To estimate the error in weekly mean flow, it is necessary to determine the spatial variability of the six down-channel velocities about their mean. For each 7-day period, the variance about the mean flow is calculated (Table 2). The average variance for all 7-day periods, 29.83 cm^2 s^{-2}, is an estimate of the spatial variability of down-channel velocities. Because the current fluctuations are spatially independent, the error in weekly mean flow can be estimated to be $(29.83/6)^{\frac{1}{2}}=2.2$ cm s^{-1}. This error, which is shown for the low-pass filtered time series of mean flow (Fig. 4b), can be considered to be the error in monitoring weekly mean flow from these current measurements.

An estimate of time-averaged mean flow is needed to estimate the time-averaged total transport through the Drake Passage. Averaging all down-channel velocities in Table 2 yields an estimate of time-averaged mean flow of 1.59 cm s^{-1} for the period March–October 1975. The standard error of this mean is 0.37 cm s^{-1} assuming all weekly velocities are independent. The assumption of independence, however, is invalid as inspection of velocities in Table 2 quickly reveals that nearly every velocity for mooring 4 is less than the mean, while most velocities on mooring 14 are greater than the mean. The explanation for this is that the temporal and spatial scales of independence were determined for velocity fluctuations, the velocities obtained after removing the record-length averaged velocities. While the fluctuations are independent at each mooring every 7 days, the record-length average for a particular mooring may bias the velocities to be consistently larger or smaller than the time-averaged mean flow. Thus, estimating the error in time-averaged mean flow by the standard error of all weekly velocities yields an error which is too small.

To estimate the error in time-averaged mean flow in a consistent manner, the time-averaged down-channel velocity is estimated for each of the six records (Fig. 5). The error in each of these time averages is estimated by the standard error of the time-averaged velocity, i.e., by taking the square root of the temporal variance divided by the number of independent time periods in each record. The time-averaged mean

TABLE 2. Seven-day down-channel (62°T) velocity components for each current meter near 2700 m depth versus time. For each 7-day period, the mean of the six velocities and the variance about that mean is calculated. The time-average of this variance is 29.83 cm^2 s^{-2}.

	Stations							
Date	2 (cm s^{-1})	4 (cm s^{-1})	8 (cm s^{-1})	10 (cm s^{-1})	12 (cm s^{-1})	14 (cm s^{-1})	Mean (cm s^{-1})	Variance (cm^2 s^{-2})
4 3 75	−4.67	−2.82	1.37	2.52	1.78	5.09	0.54	13.05
11 3 75	−7.32	−6.03	0.85	2.46	−4.07	5.99	−1.35	27.64
18 3 75	−2.58	−6.49	2.16	3.29	1.06	4.35	0.30	16.76
25 3 75	−4.75	−1.67	5.20	3.08	0.60	3.62	1.01	13.83
1 4 75	6.53	−5.22	6.48	3.47	2.26	1.82	2.56	18.62
8 4 75	9.18	−0.91	5.52	4.29	2.57	−0.14	3.42	14.10
15 4 75	8.24	0.64	2.34	4.40	0.45	3.12	3.20	8.33
22 4 75	5.04	−1.21	3.46	7.02	1.54	7.07	3.82	10.58
29 4 75	2.39	−1.14	0.31	5.08	0.37	11.51	3.09	21.68
6 5 75	−0.81	1.62	−7.59	4.22	0.36	8.73	1.09	29.62
13 5 75	2.73	−2.75	−2.07	3.35	2.07	7.98	1.89	15.45
20 5 75	0.64	−0.43	1.03	3.21	0.73	10.07	2.54	15.01
27 5 75	0.44	−0.94	3.73	0.95	2.02	9.70	2.65	14.38
3 6 75	−4.81	−1.43	1.11	0.17	0.28	5.22	0.09	10.74
10 6 75	−4.52	−0.80	3.07	0.30	0.40	6.95	0.90	14.84
17 6 75	12.27	−4.95	3.70	1.08	0.80	4.63	2.92	32.14
24 6 75	20.61	−8.87	1.89	1.59	1.17	0.01	2.73	93.25
1 7 75	11.75	−1.62	4.55	−0.37	−0.13	4.62	3.13	24.81
8 7 75	10.52	−1.49	4.11	0.82	0.67	10.43	4.18	26.99
15 7 75	14.60	1.56	4.41	4.69	−3.07	2.91	4.18	33.98
22 7 75	−13.22	−2.46	5.74	12.15	−5.44	10.59	1.23	98.79
29 7 75	−12.77	−2.19	7.33	−2.29	7.05	2.59	−0.05	56.63
5 8 75	−4.70	−4.12	12.45	3.45	1.76	3.93	2.13	39.45
12 8 75	21.50	−3.41	8.18	1.73	2.75	10.07	6.80	75.05
19 8 75	−6.02	−5.23	6.79	3.90	−5.15	9.99	0.71	49.64
26 8 75	−3.67	−1.48	7.61	3.62	−2.67	4.53	1.32	20.77
2 9 75	−15.87	−5.01	4.52	−2.21	1.88	0.51	−2.70	52.46
9 9 75	−15.10	−0.55	3.92	1.45	1.45	−1.79	−1.77	46.45
16 9 75	−9.49	0.92	5.44	4.94	1.32	−3.46	−0.06	31.71
23 9 75	−2.55	−1.69	4.63	3.23	−0.16	1.44	0.82	7.85
30 9 75	−1.77	0.15	4.65	3.06	0.03	4.66	1.80	7.30
7 10 75	1.88	0.08	7.26	2.59	−0.92	8.68	3.26	15.06
14 10 75	−1.42	−1.23	2.28	2.86	0.25	5.50	1.37	7.18
21 10 75	−16.65	−2.61	3.43	4.09	0.79	1.74	−1.54	60.39
28 10 75	−8.24	−1.63	2.58	−0.87	4.57	0.61	−0.50	19.54

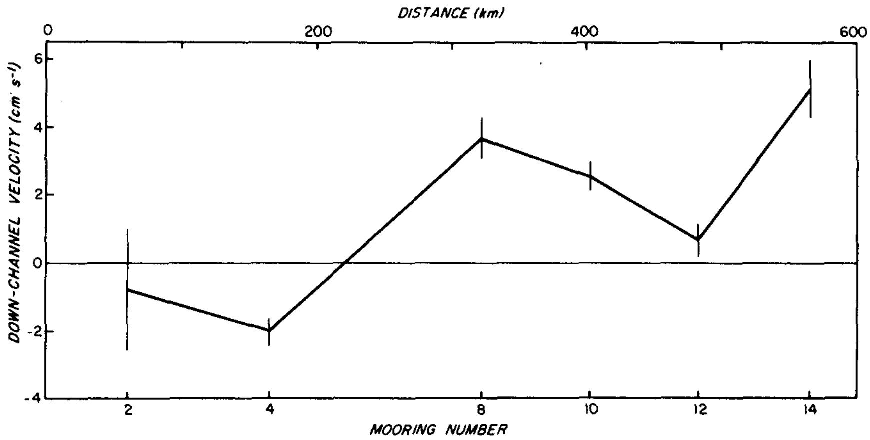

FIG. 5. Time-averaged down-channel velocities and their errors for the six long-term current meters. Each velocity is a record-length average. Each error is determined by dividing the temporal variance about the mean due to low-frequency variability by the number of independent time periods in each record.

flow is estimated to be 1.56 cm s^{-1} by taking the average of the six time-averaged velocities. This time-averaged mean flow is slightly different from the time-averaged mean flow for the period March–October 1975, estimated above, because it includes currents recorded during the period beyond the shortest common measurement period for the six records of 250 days. The error in this time-averaged mean flow due to the temporal variability of the currents is estimated to be 0.90 cm s^{-1} by averaging the temporal variability of the six records. The error in time-averaged mean flow due to spatial variability is estimated by the standard error of the six time-averaged velocities about their average to be 1.13 cm s^{-1}. Thus, the time-averaged mean flow has a total estimated error of $(0.90^2+1.13^2)^{\frac{1}{2}}=1.44$ cm s^{-1}.

3. Results and discussion

The most striking feature of the time series of mean down-channel flow at 2700 m (Fig. 4b) is its large temporal variability. The mean flow varies from 7.6 cm s^{-1} eastward (62°T) to -2.9 cm s^{-1} westward (242°T) with a typical time scale of 15 days. Based on an estimated error of 2.2 cm s^{-1} due to the spatial variability of the velocities being averaged, there are two periods, during May and August, when the mean flow is significantly different from zero at a 95% confidence level. During these periods the mean flow is eastward and at no time is there significant westward flow. If the geostrophic transport relative to 2700 m is constant in time, as suggested by the results of previous investigators (e.g., Nowlin *et al.*, 1977), the temporal variations in mean flow can be used to estimate temporal variations in total transport through the Drake Passage. A depth-averaged mean flow of 1 cm s^{-1} in the Drake Passage is equal to a transport of 25 sverdrups. With a geostrophic transport relative to 2700 m depth of 100 sverdrups, the total eastward transport varies from 28 to 290 sverdrups for a variation in transport of 262 sverdrups. This variation is twice as large as the temporal variation suggested by McKee (1971) from an analysis of sea level fluctuations on either side of the Drake Passage.

An argument can be made that the true temporal variation of the mean flow is much smaller than the variability in mean flow observed here. The standard deviation of the time series of mean flow (Fig. 4b) about its time average is 2.0 cm s^{-1} which is comparable with the expected error of 2.2 cm s^{-1} in weekly mean flow due to the spatial variability in the six current records. All the temporal variability, then, may be the result of errors in estimating the mean flow. We feel, however, that the persistence of features in the mean flow over periods of order one month suggests that large variations in mean flow, and hence in transport, do occur. The range of variation of the mean flow, however, is difficult to estimate since extreme values of mean flow may be due to extreme values of the errors. Because of this difficulty, the standard deviation of the time series of mean flow about its time-averaged value (2.0 cm s^{-1}), rather than the range of variation, is used to estimate the temporal variability of the mean flow at 2700 m.

These estimates of mean flow are consistent with the earlier short-term measurements. For Reid and Nowlin's (1971) measurements, the mean current at 2700 m depth is estimated by geostrophically extrapolating their observed currents to 2700 m depth and averaging. Based on the estimate of error due to spatial variability presented above, their mean flow of 6.8 cm s^{-1} has an error of ±2.4 cm s^{-1}. For Foster's (1972) measurements, the mean flow at 2700 m is estimated by interpolating his current measurements at 1500 and 3400 m depths to 2700 m depth and averaging. His mean flow of -3.5 cm s^{-1} has an error of ± 2.7 cm s^{-1}. For Nowlin *et al.*'s (1977) measurements, the mean flow of 0.75 cm s^{-1} has an error of ± 1.6 cm s^{-1}. Only the mean flow of Foster (1972) is slightly outside the range of variability in mean flow observed here, but it is not significantly outside the observed range. Thus the range of temporal variability in the mean flow estimated here (Fig. 4b) effectively includes the currents reported by Reid and Nowlin (1971), Foster (1972) and Nowlin *et al.* (1977). If the geostrophic transport relative to a fixed reference level is constant, the wide variation in estimates of total transport by Reid and Nowlin, Foster and Nowlin *et al.* can be accounted for by the temporal variability of these currents measured over a one-year period in the Drake Passage.

From the time-averaged down-channel velocities of the six long-term current records (Fig. 5), the time-averaged mean flow at 2700 m is estimated to be 1.56 cm s^{-1} with an error of ± 1.44 cm s^{-1}. This value can be used to narrow the range of acceptable values for mean transport through the Drake Passage with which models of the Circumpolar Current can be compared. Referencing the geostrophic transport of 100 sverdrups relative to 2700 m (Nowlin *et al.*, 1977) with the estimate of time-averaged mean flow at 2700 m yields an estimate for the time-averaged total transport of 139 ± 36 sverdrups.

Time-averaged velocity vectors for the six current records (Fig. 6) have large cross-channel, or "northward" (332°T), components. An analysis, similar to that for down-channel velocities described above, indicates that the temporally and spatially averaged cross-channel velocity is 1.83 cm $\mathrm{s}^{-1} \pm 1.49$ cm s^{-1}. This suggests that larger total transports might be estimated if a different orientation for down-channel direction were chosen. To investigate the nature of the cross-channel and down-channel velocities, the record-length averaged velocities for the three current meters on mooring 10 are examined (Fig. 7). The cross-channel velocity is nearly depth-independent or barotropic. As determined by a least-squares linear fit of the three velocities, the vertical shear of velocity has direction within 5.2° of the down-channel direction chosen here. Thus, the orientation of the hydrographic sections of Nowlin *et al.* (1977) appears to be optimal for estimating maximum time-averaged geostrophic transport. If the cross-channel velocities at other moorings are barotropic as at mooring 10, however, the average cross-channel velocity would indicate an additional barotropic transport of 46 ± 37 sverdrups "northward" so that the total transport of the Circumpolar Current would be 146 $[=(139^2+46^2)^{\frac{1}{2}}] \pm 52$ sverdrups directed 18° $[=\tan^{-1}(46/139)]$ north of the down-channel direction chosen here, that is toward 46°T.

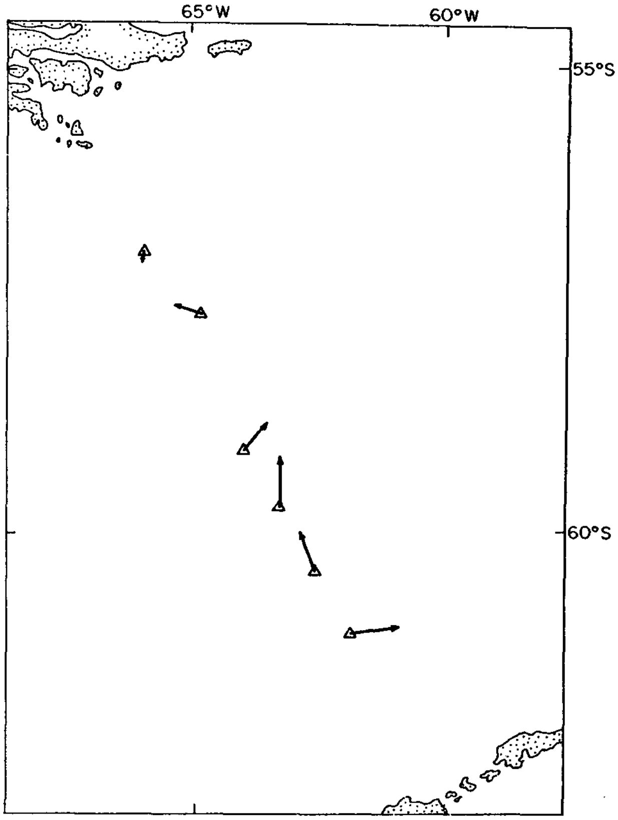

Fig. 6. Record-length averaged velocity vectors for each of the six long-term current meters at 2700 m.

These estimates of spatial and temporal variability suggest what minimum errors might be achieved in future programs for monitoring weekly mean flow and for estimating time-averaged mean flow. In this study, the largest errors in estimating mean flow were due to the spatial variability of the currents. More current records, rather than longer current records, are needed to reduce the errors. Since the error in weekly

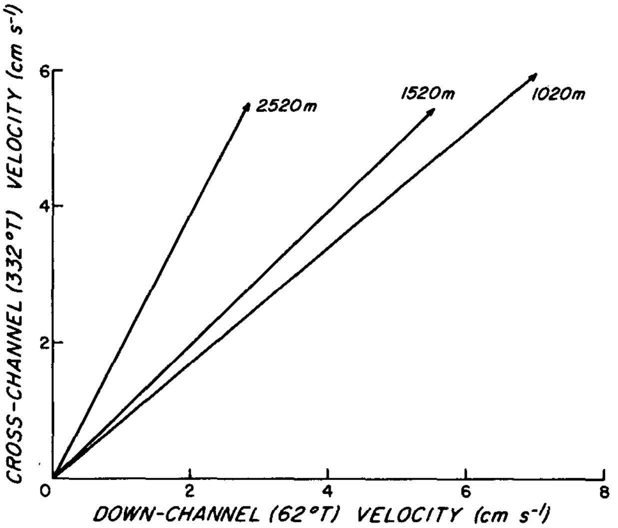

Fig. 7. Time-averaged velocity vectors for the three current meters at 1020, 1520 and 2520 m depths on mooring 10.

mean flow at 2700 m due to spatial variability is estimated to be 5.46 cm $s^{-1}/N^{\frac{1}{2}}$, where N is the number of independent current measurements, the requirement is to maximize N in order to minimize the error. Observations in the MODE region (Bretherton, 1975) and at Site D (Thompson, 1977) suggest that currents vary over spatial scales of about the Rossby radius of deformation. With an assumption that independent current measurements can be made every two Rossby radii, about 35 km in the Drake Passage, the maximum number of independent current measurements possible across the Drake Passage is 20. The minimum error in monitoring weekly mean flow at 2700 m then is 1.2 cm s^{-1} and a minimum error in monitoring weekly transport is 30 sverdrups. Based on the observed spatial variability of the record-length averaged velocities and their errors, the time-averaged mean flow during a one-year period could be estimated with an error of 1.1 cm s^{-1} or time-averaged transport within 27 sverdrups from 20 independent current records.

Because the estimate of time-averaged total transport presented here has a well-defined error which is only about 30% of the total transport, it should help modellers to test their predictions of Antarctic Circumpolar Current transport and to refine their models to include all important dynamical processes. The large temporal and spatial variability of the observed velocities suggests that models which include currents which vary over small spatial scales and short temporal scales may be necessary to understand the dynamics of the Circumpolar Current.

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REFERENCES

Bretherton, F. P., 1975: Recent developments in dynamical oceanography. *Quart. J. Roy. Meteor. Soc.*, **101**, 705–721.

Davis, R. E., 1976: Predictability of sea surface temperature and sea level pressure anomalies over the North Pacific Ocean. *J. Phys. Oceanogr.*, **6**, 249–266.

Fofonoff, N. P., 1955: A theoretical study of zonally uniform oceanic flow. Ph.D. thesis, Brown University, 46 pp.

Foster, L. A., 1972: Current measurements in the Drake Passage. M.S. thesis. Dalhousie University, 61 pp.

Gill, A. E., and K. Bryan, 1971: Effects of geometry on the circulation of a three-dimensional southern-hemisphere ocean model. *Deep-Sea Res.*, **18**, 685–721.

Gordon, A. L., 1967: Geostrophic transport through the Drake Passage. *Science*, **156**, 1732–1734.

McKee, W. D., 1971: A note on the sea level oscillation in the neighbourhood of the Drake Passage. *Deep-Sea Res.*, **18**, 547–549.

Mooers, C. N. K., L. M. Bogert, R. L. Smith and J. G. Pattullo, 1968: A compilation of observations from moored current meters and thermographs (and of complementary oceanographic and atmospheric data), Volume II: Oregon continental shelf, August–September 1966. Ref. 68-5, Dept. of Oceanography, Oregon State University, 92 pp.

Munk, W. H., and E. Palmén, 1951: Note on the dynamics of the Antarctic Circumpolar Current. *Tellus*, **3**, 53–55.

Nowlin, W. D., Jr., T. Whitworth, III and R. D. Pillsbury, 1977: Structure and transport of the Antarctic Circumpolar Current at Drake Passage from short-term measurements. *J. Phys. Oceanogr.*, **7**, 788–802.

Reid, J. L., and W. D. Nowlin, Jr., 1971: Transport of water through the Drake Passage. *Deep-Sea Res.*, **18**, 51–64.

Thompson, R. O. R. Y., 1977: Observations of Rossby waves near site D. *Progress in Oceanography*, Vol. 7, Pergamon (in press).