On the sampling timescale required to reliably monitor interannual variability in the Antarctic circumpolar transport

Michael P. Meredith[1] and Chris W. Hughes
Proudman Oceanographic Laboratory, Liverpool, UK

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[1] Numerous field programs have been conducted with the intention of monitoring the transport variability of the Antarctic Circumpolar Current (ACC). Some programs are ongoing, with further efforts planned. Here we address, for the first time, the sampling frequency required for reliable monitoring of the ACC at interannual periods. We find that, for all practical purposes, sampling with a frequency significantly higher than weekly is required to obtain reliable annual means; coarser sampling leads to serious aliasing and degradation of the true temporal progression of transport. Monitoring changes in the seasonality of the ACC requires even more rapid sampling. In practice, hydrographic sections, repeat XBT sections and even altimetry along a single repeat groundtrack will fail to capture the true interannual variability; instead, in situ instrumentation (fixed gauges, moorings or bottom lander-based equipment) is required. Combinations of techniques may be useful, if they include data from fixed in situ sources. **Citation:** Meredith, M. P., and C. W. Hughes (2005), On the sampling timescale required to reliably monitor interannual variability in the Antarctic circumpolar transport, *Geophys. Res. Lett.*, *32*, L03609, doi:10.1029/2004GL022086.

1. Introduction

[2] The Antarctic Circumpolar Current (ACC) is a key component of the global climate system. It flows clockwise around the Antarctic continent, constituting a vital link between the Atlantic, Pacific and Indian Oceans, and is responsible for the transport of large quantities of heat, salt, freshwater, nutrients, and so on. Changes in the transport of the ACC have the potential to exert significant influences on climate over large areas; hence monitoring of the ACC transport variability has long been established as a priority in the Southern Ocean.

[3] Following some early ship sections across Drake Passage that resulted in large discrepancies in transport estimates, the first major concerted effort to monitor the transport of the ACC was the International Southern Ocean Studies (ISOS) program [e.g., *Whitworth*, 1983; *Whitworth and Peterson*, 1985]. This took place in Drake Passage during the late 1970s and early 1980s, and featured a large-scale current meter mooring array across the passage, combined with several ship sections and bottom pressure recorders (BPRs) and transport moorings at either side. It produced some of the key concepts relating to the ACC, such as it being a banded structure consisting of several fast-flowing jets (e.g., Figure 1), with a mean transport of order 130 Sv (1 Sv = 10^6 m^3/s) at Drake Passage. It also generated the result that the transport variability on timescales up to around seasonal is predominantly barotropic, indicating that monitoring of ACC transport by BPRs alone might be appropriate [*Whitworth and Peterson*, 1985].

[4] In the World Ocean Circulation Experiment (WOCE) era, ship sections across Drake Passage were again conducted [*Cunningham et al.*, 2003], along with sections across the other major ‘‘chokepoints’’ south of South Africa and south of Australia [e.g., *Rintoul and Sokolov*, 2001]. BPRs were deployed either side of Drake Passage [*Meredith et al.*, 1996, 1997] and at the other chokepoints, and programs of repeat expendable bathythermographs (XBTs) were instituted. The usefulness of satellite altimetry in monitoring transport variability was also investigated [*Woodworth et al.*, 1996].

[5] Since ISOS and WOCE, much more has been learned about the nature of the circumpolar transport variability in the Southern Ocean. It is now known that this transport variability is forced by fluctuations in the Southern Annular Mode (SAM), the dominant mode of climate variability in the extra-tropical Southern Hemisphere [*Thompson and Wallace*, 2000; *Thompson et al.*, 2000]. Strong coherence between the SAM and tide gauge measurements right around Antarctica has been demonstrated [*Aoki*, 2002]; this was extended by [*Hughes et al.*, 2003] to include coherence with Drake Passage transport from OCCAM (a global ocean general circulation model), and BPR measurements. The SAM has been changing in recent decades, moving toward a high-index state (stronger circumpolar westerly winds). This trend is not purely monotonic, but is strongly modulated by season [*Thompson and Solomon*, 2002]; there is also significant interannual variability in the SAM. *Meredith et al.* [2004] showed that the interannual variability in the SAM causes interannual changes in the ocean transport through Drake Passage, and, importantly, that the interannual changes in the seasonal signal in the SAM are reflected in changes in the seasonal signal in the ACC transport.

[6] Many of the field programs instituted during WOCE and the post-WOCE era are continuing, including repeat hydrographic sections, repeat XBT sections [e.g., *Sokolov et al.*, 2004; *Sprintall*, 2003] and measurements by BPRs and tide gauges. Plans are afoot for further monitoring using combinations of current meter moorings and satellite altimetry, and enhanced measurement at the ACC chokepoints during the International Polar Year (2007–8). *Meredith et al.* [2004] showed that once-per-year estimates of transport from hydrographic sections are not adequate for monitoring interannual variability in ACC transport, since they are

[1]Now at British Antarctic Survey, Cambridge, UK.

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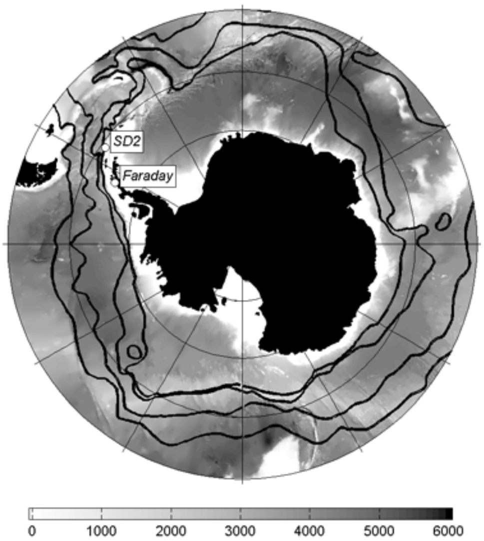

Figure 1. Schematic diagram of the fronts of the Antarctic Circumpolar Current, derived from *Orsi et al.* [1995]. Marked are the positions of the tide gauge at Faraday/Vernadksy, and the Bottom Pressure Recorder at SD2 (south Drake Passage).

badly aliased by higher-frequency (e.g., eddy) variability. However, we did not answer the question of what temporal sampling was required to monitor reliably the interannual changes in the ACC, and which techniques might be appropriate in this role. As *Gille and Hughes* [2001] showed, high frequency variability can produce significant aliased signals even with 10-day altimeter sampling, at a number of places including Drake Passage; we might thus expect aliasing to be a significant issue in designing a transport monitoring system. We address these issues now.

2. Data

[7] For this study, we used sea level data from Faraday Station (now operated by the Ukraine, and renamed Vernadsky) on the west side of the Antarctic Peninsula (Figure 1). The tide gauge at Faraday consists of a conventional float gauge housed within a heated stilling well. It has provided data since 1958, as part of the UK's contribution to IGY activities. Sea level data were combined with air pressure data to produce a time series of subsurface pressure (SSP; sea level corrected for the inverse barometer effect) for the period 1988–2002. Data were detided, and daily mean values calculated. It has been shown previously that data from here reliably reflect changes in the circumpolar transport around Antarctica from timescales of days [*Aoki*, 2002; *Hughes et al.*, 2003] up to years [*Meredith et al.*, 2004]. However, the seasonal signals in Faraday SSP are unlikely to reflect reliably the ACC transport variability, since other processes (ice formation/melting, upper ocean steric effects etc) operate at the same frequency.

[8] To investigate the effects of aliasing on derived interannual changes in the seasonality of the ACC, we used data from BPRs deployed at around 1000-m depth at the south side of Drake Passage (the SD2 position; Figure 1). BPRs were deployed typically for 1–2 years duration prior to turnaround. The individual series were concatenated using endpoint matching, detided, and variability at timescales longer than annual was removed. Combined, the Faraday and SD2 BPR data provide the best observational dataset for studying sampling intervals and the ACC. A drawback of these data, however, is that they only provide indices of transport variability, not quantification in sverdrups.

[9] We have also made use of a time series of ACC transport from the $^1/_4°$ OCCAM general circulation model [*Webb et al.*, 1998], forced with 6-hourly winds and atmospheric pressures from the ECMWF reanalysis. Despite the potential shortcomings of ocean models, it has been demonstrated previously that OCCAM captures well the variability in circumpolar transport for timescales from days to years [*Hughes et al.*, 2003; *Meredith et al.*, 2004]. The real ocean is, of course, likely to be no less complex than the OCCAM ocean; thus if the OCCAM ACC cannot be reliably monitored with a given sampling interval, it is likely that the real ACC cannot be either. The OCCAM transport time series is available at 2 day intervals, for the period 1992–2000.

3. Results

[10] To determine the sampling timescales for which interannual variability in transport could reliably be derived, we subsampled the Faraday SSP and OCCAM transport at a range of intervals, separately for each of the years of data coverage. We then calculated the difference between the apparent annual mean (derived from the subsampled series) and the true annual mean, again for each year separately.

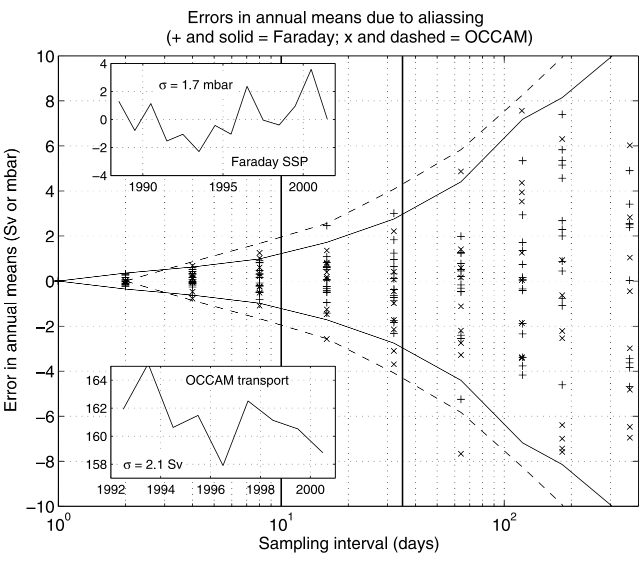

Figure 2. Errors in derived annual means of Faraday SSP (plusses) and OCCAM transport (crosses) due to aliasing, plotted as a function of sampling interval. The "envelopes" are ± twice the standard deviation of the errors for each sampling interval, corresponding to the 95% confidence interval (solid for Faraday SSP, dashed for OCCAM transport). The two insets show the progressions of true annual means of Faraday SSP and OCCAM transport, which have standard deviations of 1.7 mbar and 2.1 Sv respectively. The solid vertical lines are at 10 days and 35 days, corresponding to the repeat periods of the TOPEX/JASON and ERS/Envisat satellite altimeters.

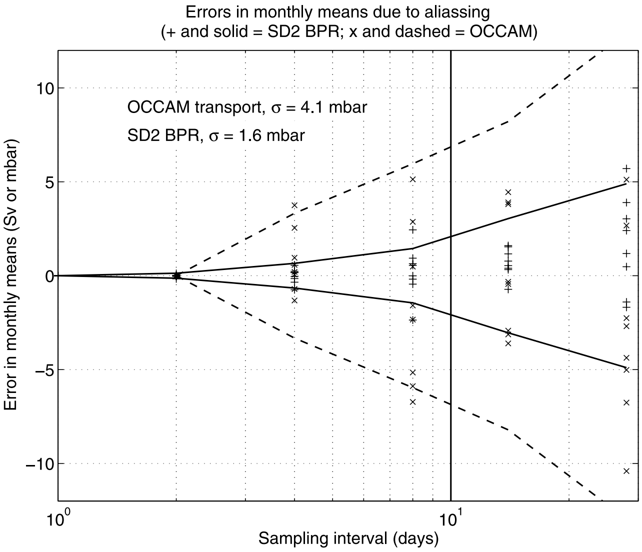

Figure 3. Errors in derived interannual variability of monthly means of SD2 bottom pressure (plusses) and OCCAM ACC transport (crosses) due to aliasing, plotted as a function of sampling interval. The "envelopes" are ± twice the standard deviation of the errors for each sampling interval, corresponding to the 95% confidence interval (solid for SD2, dashed for OCCAM). The solid vertical lines are at 10 days and 35 days, corresponding to the repeat periods of the TOPEX/JASON and ERS/Envisat satellite altimeters.

For each sampling interval, all possible initial days were considered (e.g., for the Faraday daily time series, subsampled at 4-day intervals, there are 4 possible initial days generating 4 different subsampled time series).

[11] Figure 2 shows, for one particular initial day, the errors in derived annual means of Faraday SSP, plotted as a function of sampling interval. (The upper inset is the progression of true annual means of Faraday SSP, which has a standard deviation of 1.7 mbar). The solid line "envelope" shown is ± twice the standard deviation of the errors for each sampling interval, corresponding to the 95% confidence interval (note that the envelope plotted is the average envelope for all possible initial days). From this diagram, it can be seen that if one wishes to sample the annual means of Faraday SSP to a level equivalent to that of the standard deviation of the actual series, sampling at around 10 days or better is required. The solid vertical lines are at 10 days and 35 days, corresponding to the repeat periods of the TOPEX/JASON and ERS/Envisat satellite altimeters. It can be seen that the 10 day repeat barely resolves the transport variability to the required level of accuracy, whereas the 35 day repeat is badly aliased.

[12] Figure 2 also shows the corresponding analysis performed using the OCCAM transport time series. (The $\pm 2\sigma$ envelopes for the OCCAM series are plotted as dashed lines; the lower inset shows the genuine progression of annual mean OCCAM transports). Again, it can be seen that to resolve the interannual variability in transport at a level commensurate with the standard deviation in the actual series (2.1 Sv, in this case), sampling at around 10 days or better is required.

[13] It was shown by *Meredith et al.* [2004] that the seasonality of the ACC transport changed significantly during the 1990s, due to changes in climatic forcing. This raises the question of what sampling interval is required to monitor reliably the changing seasonality of the ACC. Figure 3 shows analyses corresponding to those given above, but where we have investigated aliasing of interannual variability in monthly means rather than annual means. For this, we used the SD2 BPR series rather than the Faraday SSP series, for reasons given previously. It can be seen that, to monitor the changing seasonality of the SD2 BPR data at a level commensurate with its standard deviation (1.6 mbar), sampling at around 8 days or better is required. The corresponding analysis of OCCAM transport indicates an even higher sampling requirement (Figure 3), around 5 days or better.

[14] A different view of these issues is seen in Figure 4. This shows the average correlation of the apparent interannual variability in Faraday SSP (derived from the subsampled time series) with the actual interannual variability (the original time series), plotted as a function of sampling interval. The average is taken over all possible initial days, for each sampling interval. The equivalent curve for OCCAM annual mean transports is also plotted. The similarity of the curves is striking, adding confidence that they are both good measures of at least the statistics of

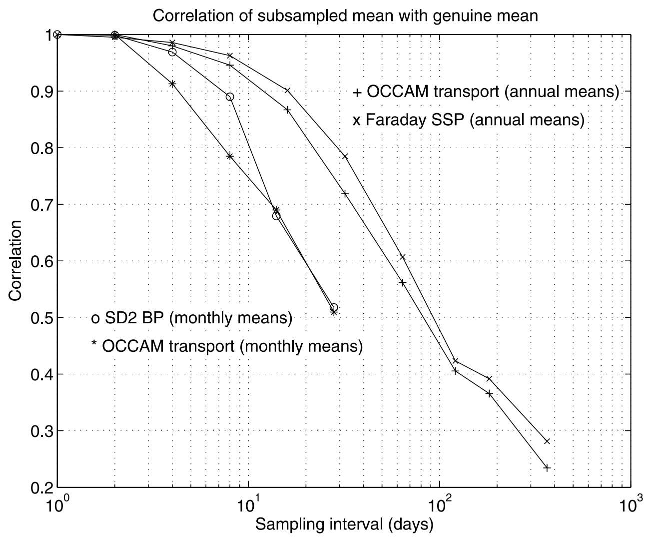

Figure 4. x = correlation of apparent interannual variability in Faraday SSP (derived from the subsampled time series) with the actual interannual variability, plotted as a function of sampling interval; + = equivalent for OCCAM transport. Note that at 30 days, only around half the variability observed in the subsampled annual mean time series can be ascribed to actual transport variability (half the variance explained corresponds to a correlation of $(1/\sqrt{2}) = 0.707$); the rest is the result of aliasing. o = correlation of apparent interannual variability of monthly means from SD2 BPR (derived from the subsampled time series) with the actual interannual variability in the monthly means; * = equivalent for OCCAM transport. Beyond 15 days, less than half of the interannual variability in the monthly means is due to actual transport variability; the rest of the result of aliasing.

variability in the ACC on these timescales. For a sampling interval of 30 days, only around half the variance observed in the subsampled time series can be ascribed to actual transport variability (half the variance explained corresponds to a correlation of $(1/\sqrt{2}) = 0.707$); the rest is the result of aliasing. To produce an interannual series of ACC transport variability accurate at the 5–10% level requires sampling more frequently than every 10 days, consistent with the results presented above.

[15] Figure 4 also shows the corresponding analysis for interannual changes in the seasonality of the ACC transport (the curves for SD2 and OCCAM monthly means). It can be seen that, to monitor the changes reliably at the 90–95% level, one needs sampling better than around 8 days (as indicated by SD2) or better than around 5 days (as indicated by OCCAM).

4. Conclusions

[16] We have seen that, due to sampling considerations alone, monitoring of interannual variability in ACC transport requires sampling with an interval shorter than 10 days. This presumes that the transport can be measured perfectly at each realization, i.e., that there is zero measurement error. In reality, of course, even small measurement errors ($\sim$2 Sv in transport) will greatly impact on the accuracy of the final series produced. This implies that even more rapid sampling is required, so that more samples are obtained and hence measurement errors will be averaged out to some extent. To monitor the changing seasonality of the ACC requires more rapid sampling still; despite the larger signals present in transport at this frequency, the shorter period leads to fewer samples per wavelength for a given sampling interval, and hence more significant aliasing.

[17] For all practical purposes then, sampling with a frequency significantly higher than weekly is required. Repeat hydrographic sections clearly cannot meet this requirement; similarly repeat XBT sections are unlikely ever to be conducted with this frequency. Satellite altimeter data along repeat groundtracks also do not meet this sampling requirement; although the TOPEX/Jason 10-day repeat has a sampling interval approaching that required, the measurement error (at least 4 cm root-mean-square noise along a single pass in the Southern Ocean) will swamp the genuine transport signal. While the altimetric sampling can be increased by considering more than one track, in practice the region of strong correlation with ACC transport is intermittently under ice for almost all tracks, leading to strong seasonal aliasing. We find that, for all practical purposes, monitoring of interannual variability in ACC transport requires in situ instrumentation, deployed on moorings, bottom landers, or fixed gauges. Other techniques may add useful information, but do not circumvent this requirement. Future monitoring, such as that planned for the International Polar Year, should take this requirement into consideration.

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References

Aoki, S. (2002), Coherent sea level response to the Antarctic Oscillation, *Geophys. Res. Lett.*, *29*(20), 1950, doi:10.1029/2002GL015733.

Cunningham, S. A., S. G. Alderson, B. A. King, and M. A. Brandon (2003), Transport and variability of the Antarctic Circumpolar Current in Drake Passage, *J. Geophys. Res.*, *108*(C5), 8084, doi:10.1029/2001JC001147.

Gille, S. T., and C. W. Hughes (2001), Aliasing of high-frequency variability by altimetry: Evaluation from bottom pressure recorders, *Geophys. Res. Lett.*, *28*(9), 1755–1758.

Hughes, C. W., P. L. Woodworth, M. P. Meredith, V. Stepanov, T. Whitworth, and A. R. Pyne (2003), Coherence of Antarctic sea levels, Southern Hemisphere Annular Mode, and flow through Drake Passage, *Geophys. Res. Lett.*, *30*(9), 1464, doi:10.1029/2003GL017240.

Meredith, M. P., J. M. Vassie, K. J. Heywood, and R. Spencer (1996), On the temporal variability of the transport through Drake Passage, *J. Geophys. Res.*, *101*, 22,485–22,494.

Meredith, M. P., J. M. Vassie, R. Spencer, and K. J. Heywood (1997), The processing and application of inverted echo sounder data from Drake Passage, *J. Atmos. Oceanic Technol.*, *14*(4), 871–882.

Meredith, M. P., P. L. Woodworth, C. W. Hughes, and V. Stepanov (2004), Changes in the ocean transport through Drake Passage during the 1980s and 1990s, forced by changes in the Southern Annular Mode, *Geophys. Res. Lett.*, *31*, L21305, doi:10.1029/2004GL021169.

Orsi, A. H., T. Whitworth, and W. D. Nowlin (1995), On the meridional extent and fronts of the Antarctic Circumpolar Current, *Deep Sea Res., Part I*, *42*(5), 641–673.

Rintoul, S. R., and S. Sokolov (2001), Baroclinic transport variability of the Antarctic Circumpolar Current south of Australia (WOCE repeat section SR3), *J. Geophys. Res.*, *106*(C2), 2815–2832.

Sokolov, S., B. A. King, S. R. Rintoul, and R. L. Rojas (2004), Upper ocean temperature and the baroclinic transport stream function relationship in Drake Passage, *J. Geophys. Res.*, *109*, C05001, doi:10.1029/2003JC002010.

Sprintall, J. (2003), Seasonal to interannual upper-ocean variability in the Drake Passage, *J. Mar. Res.*, *61*, 27–57.

Thompson, D. W. J., and S. Solomon (2002), Interpretation of recent Southern Hemisphere climate change, *Science*, *296*, 895–899.

Thompson, D. W. J., and J. M. Wallace (2000), Annular modes in the extratropical circulation. Part I: Month-to-month variability, *J. Clim.*, *13*, 1000–1016.

Thompson, D. W. J., J. M. Wallace, and G. C. Hegerl (2000), Annular modes in the extratropical circulation. Part II: Trends, *J. Clim.*, *13*, 1018–1036.

Webb, D. J., et al. (1998), The first main run of the OCCAM Global Ocean Model, *Internal Doc. 34*, Southampton Oceanogr. Cent., Southampton, UK. (Available at http://citeseer.ist.psu.edu/517830.html.)

Whitworth, T. (1983), Monitoring the transport of the Antarctic Circumpolar Current at Drake Passage, *J. Phys. Oceanogr.*, *13*(11), 2045–2057.

Whitworth, T., and R. G. Peterson (1985), Volume transport of the Antarctic Circumpolar Current from bottom pressure measurements, *J. Phys. Oceanogr.*, *15*(6), 810–816.

Woodworth, P. L., J. M. Vassie, C. W. Hughes, and M. P. Meredith (1996), A test of the ability of TOPEX/Poseidon to monitor flows through the Drake Passage, *J. Geophys. Res.*, *101*(C5), 11,935–11,947.

C. W. Hughes, Proudman Oceanographic Laboratory, Joseph Proudman Building, 6 Brownlow Street, Liverpool L3 5DA, UK.

M. P. Meredith, British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK. (mmm@bas.ac.uk)