The travel time measurements of the PIES/CPIES can be the time-mean velocity from a numerical model (see examples at right).

For this study, one goal was to maximize the length of time spanned for estimating a time series of the MOC at 34.5°S. As such, the analysis has focused on the two records that have been in the water for the longest contiguous period: Sites A and Z (see at left), which were both in line, defined from March 2009 and December 2013, and then again from September 2013 to July 2017. These two sites are using PIES/CPIES moorings to collect daily observations of round trip acoustic travel time and bottom pressure (at left, panels b & c).

The western site (“A”) observes more variability at all time scales for travel time (a baroclinic measure), and for all time scales below semi-annual for bottom pressure (a barotropic measure).

The daily density profiles produced by the PIES/CPIES at Sites A and Z can be integrated to give dynamic height anomaly profiles, and these can then be differentiated to yield profiles of the meridional geostrophic velocity relative to an arbitrary level of no motion (left, with a 1350 dbar level of no motion). This represents a time integration across the entire basin between the two sites.

The daily bottom pressure values from the PIES/CPIES can be differentiated to yield the time-variability of the meridional geostrophic absolute velocity at the nominal level of no motion (blue line at lower left), and if a time-mean velocity at this level is available, such as from a numerical model (magenta dashed line, derived from a 35-year run of the OFES model), then the full time-variation of meridional “reference” velocity is available.

Combining the geostrophic relative velocity profile time series with the geostrophic reference velocity time series yields a time series of the absolute geostrophic meridional velocity integrated across the basin between Sites A & Z (at right).

Another component of the meridional flow across 34.5°S is the direct wind-driven Ekman flow. This flow is small when integrated across the basin between Sites A and Z, with a mean value during March 2009-April 2017 of 2.0 Sv, but the peak-to-peak range of daily values spans nearly 12 Sv to >20 Sv. (see at left)

The Ekman results are not highly sensitive to which wind product is used, with the CCMP winds producing nearly identical time series, particularly at periods longer than 30 days.

The resulting time series of daily MOC transport estimates is highly variable, with a mean value of 14.7 Sv and a daily standard deviation of 8.3 Sv. Recall that the mean value is almost completely determined by the time-variability of the absolute “reference” velocity mean values, while the time variability of the MOC is completely independent of the model.

The MOC time series observed at 26.5°N is much larger than the 34.5°S record, and probably is more accurate as well, although the 26.5°N calculation does involve a residual term.

The two time series show no correlation, which is perhaps not surprising since the much closer 16°MOVE array has also shown little correlation with the 26.5°N array record.

The 34.5°S and 26.5°N records do show fairly similar changes on time scales ranging from days to interannual. The daily standard deviation at 34.5°S is almost twice as large as at 26.5°N, which may be due to relaxed variability estimates. Both records may also be affected by smoothing of the barotropic variability by the residual calculation at 26.5°N.

Focusing on the time variability of the MOC at 34.5°S, the peak-to-peak range exceeds 50 Sv.

The relative (baroclinic, density-driven) term has the largest contribution to the overall MOC variability, with the Ekman (wind-driven) and reference (barotropic, pressure-driven) terms having roughly equal contributions. (Daily std. devs. = 6.6, 4.7, 4.8 Sv, respectively.) Those terms are uncorrelated with each other.

The relative and reference terms are driven roughly equally by variations at the western and eastern boundary. (Daily std. devs. within ~10% east vs. west.)

Looking at interannual variations (table at right), we find that the relative contribution is significant larger, but reference terms dominate the total in about the same number of years as the relative due to canceling influences of the two boundaries. The Ekman term has very small impacts at interannual time scales when only the full-year averages are considered (i.e. ignore gray box/gray in tables where only 1 or 2 years are available for averaging).

Both the western and eastern boundaries have important contributions at the interannual time scale, although eastern boundary signals tend to be larger amplitudes.

Conclusions

- The MOC at 34.5°S is highly variable (STD = 3.3 Sv) during 2009-2017, with strong variations at time scales ranging from a few days to interannual. There is no statistically-significant trend.

- Seasonal MOC variability due to the Ekman transport is roughly 180° out of phase with the seasonal variations associated with the reference term (i.e., barotropic pressure) – as expected. As such, the seasonal cycle in the MOC is primarily driven by the relative (density) term, although the other terms do have non-trivial impacts. The seasonal cycle of the relative term is most strongly associated with the density variations at the eastern boundary.

- Interannual (year-to-year) variations are most strongly driven by relative (density) term changes, although in some years the reference (pressure) term dominates. At interannual time scales both the western and eastern boundary variations are important, although the eastern side tends to be more important for both relative and reference terms most years.

- A key takeaway of this analysis is that it is essential to measure both the relative and reference components of the MOC at 34.5°S, as both very strongly and independently, and that it is essential to measure them at both the western and eastern edges of the basin.