Insights from the search for a new AMOC index

How I took a CIRES Tuition Assistance Benefit class assignment way too far

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Introduction (science)

The remote nature of the abyssal ocean makes it difficult to investigate deep thermohaline circulation, including the Atlantic Meridional Overturning Circulation (AMOC). Many studies use paleoclimate data, reanalyses, or some combination of the two to indirectly characterize the strength of the AMOC from year to year. The relatively short record of direct and comprehensive AMOC observations makes it difficult to make strong conclusions about long-term systematic changes without other evidence.

Additionally, paleoclimate and modelling studies largely do not characterize the short term variation of the AMOC, nor do they usually describe the vertical structure of the AMOC on monthly and seasonal time scales. In the last two decades, observation systems like the RAPID array have revealed that there are interesting things occurring at those time scales, whether or not they have much bearing on the grander systematic changes occurring at longer scales.

The RAPID array is a series of moorings intended to monitor the status of the AMOC at a high frequency and resolution. It was deployed in the Atlantic at 26.5 degrees north in 2004 and has been in operation since. The RAPID team produces a very accessible, continuous and comprehensive dataset to which both physical oceanography and modern data analytics can be applied.

Over the course of this project, I aimed to use the latter to develop a new index for the AMOC, capable of describing its variation at short time scales and fully capturing its vertical structure. Success aside, here I present a set of cool (new?) insights about the AMOC, derived from the RAPID Array depth profiles.

Background (story)

As an Associate Scientist at CIRES, I am fortunate to be able to take advantage of the Tuition Assistance Benefit (TAB) through CU Boulder. While I have some training in dynamics and earth science, my primary skillsets are data science and software engineering.

So, in order to broaden my horizons and enrich my work at PSL, I joined the CU ATOC department's Descriptive Physical Oceanography (ATOC 4215) and Atmospheric Dynamics (ATOC 4720) courses. This work started as an assignment for ATOC 4215: after being introduced to the thermohaline circulation, AMOC, and the RAPID Array in class, we were asked to describe the seasonality and interannual variation of the AMOC.

Needless to say I failed to stop at that- I found exploring direct observations, without any specific agenda, to be refreshing, and kept coming back to it in my spare time.

Materials and Methods

Loosely, AMOC is characterized by the zonally integrated northward Sverdrup transport (MOC(z)) occurring in the Atlantic. This metric aggregates northward transport in both x and z dimensions, meaning information about the vertical and horizontal structure of the circulation is lost.

Searching for a way to characterize AMOC in a time series without losing the vertical structure, I applied principal components analysis to the RAPID array depth profiles, using the separate time series at different depths as separate features. The resulting first principal component explains ~92% of the variance in the RAPID array data, and corresponds approximately to the sum total of the northward Sverdrup transport, in a very similar way to MOC(z).

In fact, the Pearson Correlation coefficient between MOC(z) and RAPID PC1 is 0.99 — making RAPID PC1 a reasonable substitute for MOC(z) which can also meaningfully be disaggregated to reconstruct depth profiles of Sverdrup transport.

Many other studies use sea surface temperature (SST) in the northern Atlantic as a proxy for AMOC northward transport. It seems intuitive to me that the North Atlantic SST-Rapid Array connection would operate on a longer time frame though, because of the slow rate of Sverdrup transport associated with AMOC and large distance between the region of interest and the Rapid Array.

Monthly variations in the low-level wind, however, could be related to AMOC through a number of faster dynamical processes like Ekman transport, turbulent eddy momentum flux, or steric changes associated with increased surface level mixing.

With that in mind, I investigated the relationship between RAPID PC1 and the ERA5 surface level winds by first detrending both the RAPID data and the wind fields, then removing their climatologies and performing EOF analysis using meridional and zonal wind fields as equally-weighted features. I also explored SST and sea surface height relationships, but chose to focus on the monthly mean 1000 hPa wind fields from the ERA5 reanalysis.

This project uses the Sverdrup Transport depth profiles from the RAPID array, collected between 2004 and 2020, which are available from https://rapid.ac.uk/data.php as well as ERA5 1000 hPa wind fields which are available for download from the ECMWF.

Results

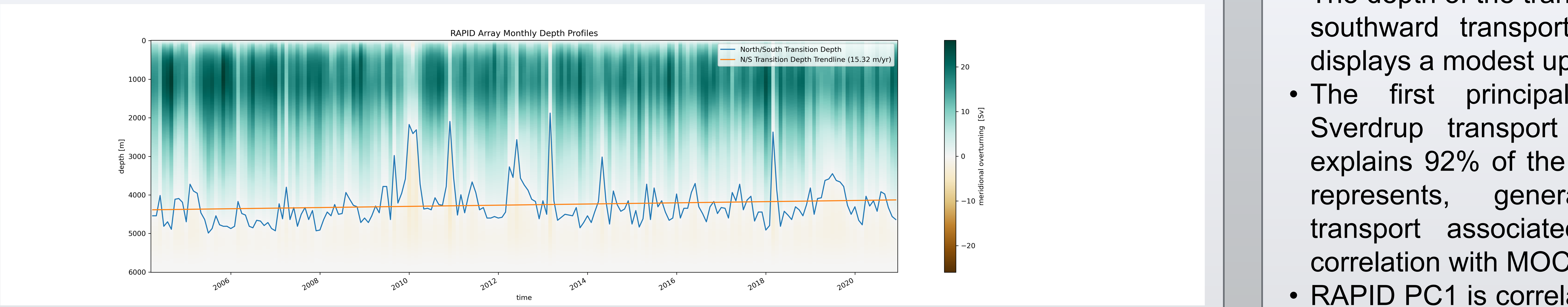


Figure 1: Sverdrup Transport depth profiles from the RAPID Array at 26.5N over time. Here the blue line highlights the depth at which Sverdrup transports switches directions from north to south with depth, and the orange line shows the linear trend in the transition depth (shoaling by 15.32 meters per year)

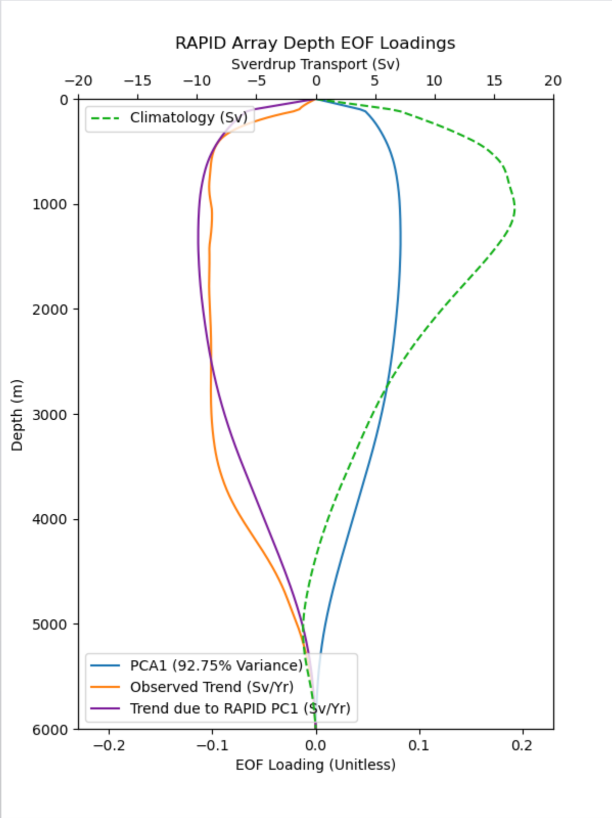


Figure 2: EOF1 Loadings for each depth, observed trend in Sverdrup transport at each depth, and trend associated with RAPID PC1 (bottom axis) overlaid with the climatological average Sverdrup transport at the RAPID array (top axis). The gradient of negative trend between upper and lower depths, combined with the shape of the climatology create, or are a product of, the negative trend in transition depth.

Figure 3: Time series of RAPID PC1 and North Atlantic 1000 hPa Wind PC1 (left y-axis) and MOC(z) (right y-axis). Trendlines for MOC(z) and RAPID PC1 are plotted in grey. Dotted lines of the same colors are plotted representing corresponding time series which have been detrended and had their seasonality removed.

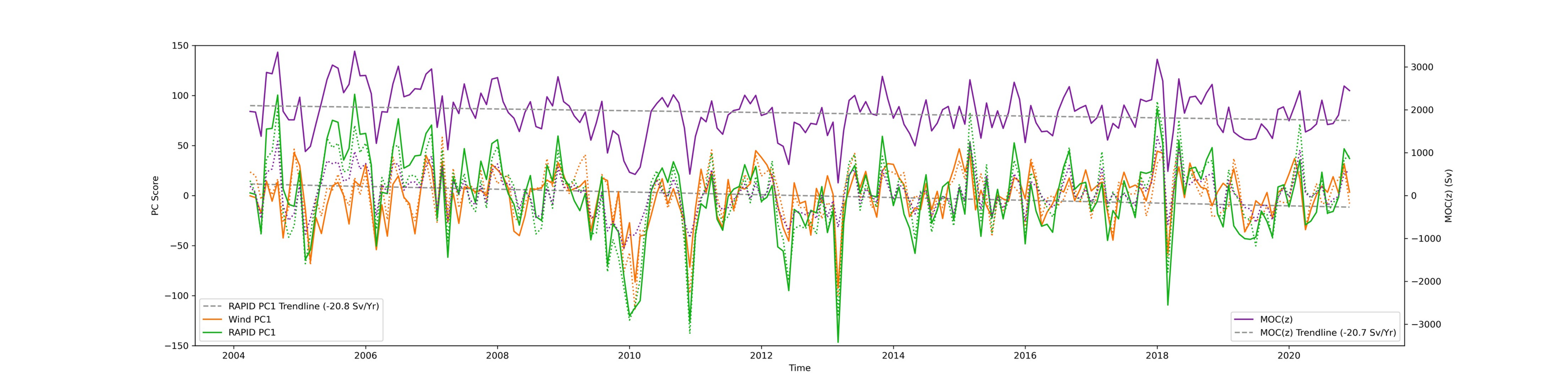
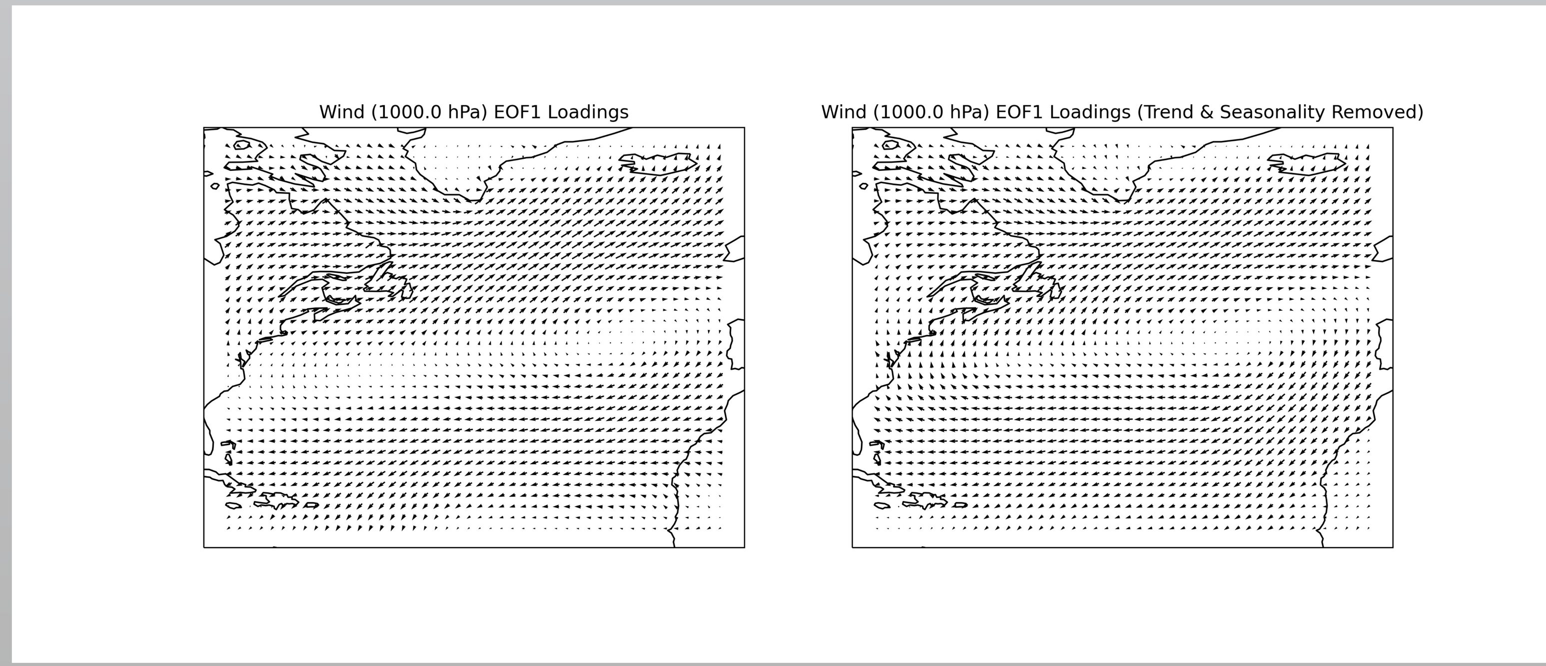


Figure 4: correlations between the time series detailed in figure 3. Correlations for detrended, anomalized versions of the time series are indicated in parentheses.

MOC(Z)	RAPID PC1	North Atlantic Wind PC1	
1.00 (1.00)	0.99 (0.97)	0.61 (0.67)	MOC(Z)
0.99 (0.97)	1.00 (1.00)	0.62 (0.69)	RAPID PC1
0.61 (0.67)	0.62 (0.69)	1.00 (1.00)	North Atlantic Wind PC1

Figure 5: EOF Loadings for the ERA5 North Atlantic 1000 hPa wind PC1, which explains about 6% of the variance in the wind fields. This leading mode is characterized by westward winds in the southern half and eastward winds in the northern half, divided approximately by the Gulf Stream.



Main Points

- The depth of the transition from northward to southward transport at the RAPID array displays a modest upward trend over time.
- The first principal component of the Sverdrup transport at the RAPID array explains 92% of the dataset's variance and represents, generally, the northward transport associated with AMOC. (0.99 correlation with MOC(z)).
- RAPID PC1 is correlated to the leading EOF mode of North Atlantic 1000 hPa wind (0.62 Pearson Coef, and even more so with trend and seasonality removed: 0.69 Pearson Coef)
- Slowing of the northward transport (RAPID PC1, or MOC(z)) could explain the upward trend in transition depth through decreased momentum flux

Next Directions

- Is the relationship between wind and Sverdrup transport due to Ekman transport? Seems likely
- Is this really a momentum flux story?
- Are RAPID-PC2 and RAPID-PC3 meaningful? What drives them?
- Modelling studies could determine whether the relationship between wind and AMOC is meaningful or spurious

Conclusions

- The CIRES Tuition Assistance Benefit is great and you should take advantage of it!
- I'm happy to help with the paperwork.

Acknowledgements & References

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