Signal and noise in the Atlantic Meridional Overturning Circulation at 26°N

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Abstract

The Atlantic Meridional Overturning Circulation (AMOC) is key to the redistribution of heat in the climate system. It is projected to weaken due to climate change. The RAPID mooring array observes the strength of the AMOC, showing an overall weakening of 1.0 Sv/decade from 2004–2023. However, the significance of this trend is controversial. Here we consider the RAPID observations in a signal-to-noise framework to understand where low frequency, climatic signals are strongest. There is a strong signal in Lower North Atlantic Deepwater (LNADW) transports. In contrast, we find little signal and significant noise in Ekman transports and in revised Gulf Stream estimates. We remove the influence of the Ekman transport on AMOC and LNADW estimates, reducing the noise by 30% and 22% respectively. We find a simple model of LNADW, based on deep hydrography on the western boundary, has a similar signal-to-noise ratio to the full AMOC estimate, showing how climate 'signal' is concentrated in the deep ocean. Understanding the sources of 'noise' and 'signal' is key to timely detection of climatic change in the AMOC and in attribution of observed changes.

Introduction

The detection of long term trends and low-frequency climatic variations in observations of the Atlantic Meridional Overturning Circulation (AMOC) is an important and at times controversial topic. Reconstructions and instrumental proxy estimates for the AMOC are numerous (Caesar et al., 2021) but their consistency and accuracy have been questioned (Kilbourne et al. 2022). These questions have not stopped these proxies being used to investigate critical and controversial questions such as whether the AMOC maybe approaching a tipping point (Boers 2021; Ditlevsen and Ditlevsen 2023).

Direct, continuous observations of the AMOC are relatively short in the context of climatic timescales, with dedicated programmes for continuous AMOC observation not beginning until the first decade of the 21st century (Frajka-Williams et al. 2019). Initial results from the RAPID-MOCHA-WBTS (hereafter RAPID) project revealed the highly variable nature of the AMOC at 26ºN on timescales from days to years (Cunningham et al. 2007; Kanzow et al. 2010; McCarthy et al. 2012; Smeed et al. 2014). RAPID has seen a range of -4.3 Sv [1 Sv = 10^6 m^3 s^{-1}] to 32.3 Sv in the AMOC (10-day filtered values) from April 2004 to January 2023.

Large variability has not stopped studies looking at trends in the AMOC. Smeed et al. (2014) found a strong weakening in the first 8 years of RAPID. The weakening AMOC in the RAPID timeseries appeared to end, with a strengthening observed from 2009/10 to 2018 (Moat et al. 2020). However, the latest data release as of September 2024, shows a weakening signal again. Such reversals in the fortune of the AMOC in the past 20 years have posed problems for the Intergovernmental Panel for Climate Change (IPCC), with a diluting in the confidence statement associated with AMOC decline between the Special Report on Ocean and Cryosphere report and 6th assessment report (see McCarthy and Caesar (2023) for discussion).

Understanding of the origins of the variability observed in the AMOC has advanced in the 20 years of RAPID observations, with seasonality (Kanzow et al. 2010; Chidichimo et al. 2010; Pérez-Hernández et al. 2015), interannual variability (McCarthy et al. 2012; Roberts et al. 2013), and the impact of the mesoscale (Evans et al. 2022; Kanzow et al. 2009) all contributing. Surprising relationships have been unearthed such as the link between Ekman transport at the surface and lower North Atlantic Deepwater properties at 3000–5000 m (Frajka-Williams et al. 2016).

Against this highly variable background, detection of anthropogenic driven changes in the AMOC has also been considered. The model study of Baehr et al. (2007) showed deep, basinwide density gradients as a sensitive estimator of AMOC decline due to lower noise in the deep ocean. The importance of deep, basinwide observations was also emphasized by the climate model results of McCarthy et al. (2017). Both studies indicate the importance of deep observations in the detection of trends in the AMOC.

A key motivation for sustained observations of the AMOC is the projection from successive generations of climate models that the AMOC will weaken in response to anthropogenic climate change. The most recent CMIP6 models estimate a projected AMOC weakening of 1 Sv/decade (Weijer et al. 2020). More abrupt, statistical estimates of collapse are associated with an approximate 5 Sv/decade AMOC decline (Ditlevsen and Ditlevsen 2023).

In the context of detection, these low-frequency weakening (or strengthening) trends can be considered the target signal for detection of change, with other observed variability being noise. In this study, we combine our knowledge of the origins of variability in the RAPID AMOC estimates in a signal-to-noise framework and consider the question of whether there are better variables than the full AMOC estimate to observe climatic AMOC decline.

Data and Methods

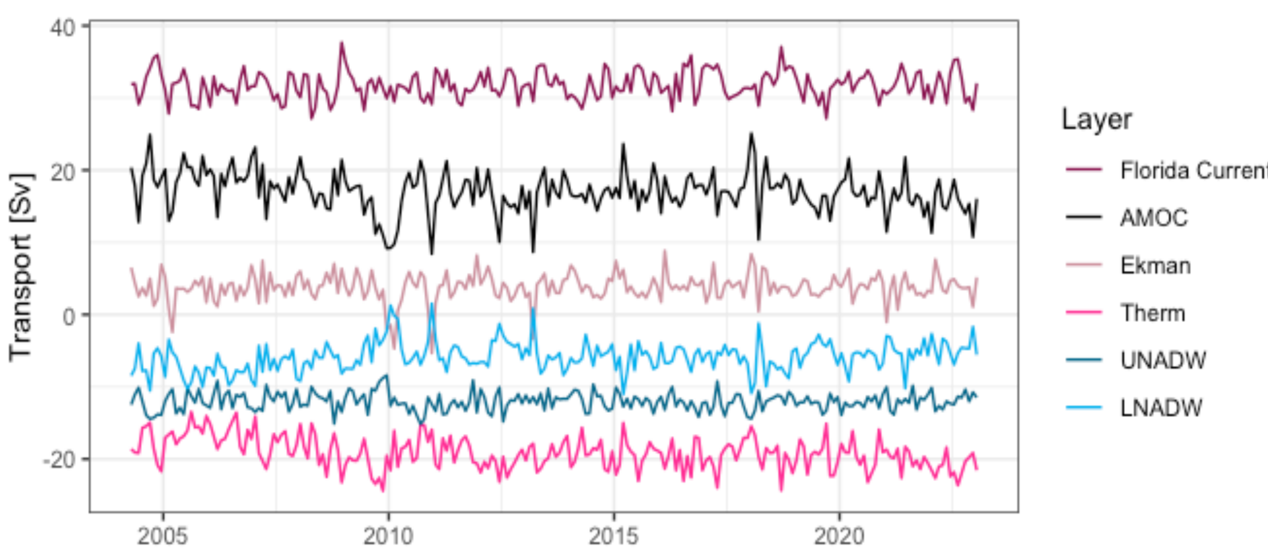

Figure 1: Monthly, deseasonalised AMOC values (black) and its components (as labelled) as observed at the RAPID array.

This study uses monthly, deseasonalised data from the RAPID array (Fig. 1, Moat et al., 2024). Monthly averages are chosen so that each observation can be considered approximately independent. Smeed et al. (2014) found a decorrelation length scale of 40 days for the deseasonalised AMOC. Using monthly, deseasonalised values, we find a similar figure of 1.5 months. The mean strength of the monthly, deseasonalised AMOC is 17.0 Sv with a standard deviation of 2.8 Sv from April 2004 to January 2023. This is an estimate of the maximum of the overturning streamfunction, the most common metric of AMOC strength.

The RAPID estimate is comprised of contributions from different components. Approximately,

$$\text{AMOC} = \text{GS} + \text{Ekman} + \text{Therm} = -(\text{UNADW} + \text{LNADW}),$$

where GS (Gulf Stream) is the represented by the northward flowing Florida Current (Meinen et al. 2010), Ekman Transport is the (typically) northward ageostrophic wind-driven transport in the upper 50 m, and the southwards thermocline (Therm) recirculation in the depth range 0 to 800m. These three layers constitute the majority of the upper, warm branch of the AMOC. The lower, cool branch of the AMOC is well-described by two southward flowing layers: Upper North Atlantic Deep Water (UNADW) from 1100 m to 3000 m, and Lower North Atlantic Deep Water (LNADW) from 3000 m to 5000 m.

As the equation above highlights, the AMOC can be approximately represented by the sum of upper, warm components (GS, Ekman, Therm) balanced by the deep, cold components (LNADW, UNADW, Fig. 2). Linear regression shows this quantitively, with the upper, warm (deep, cold) components strongly related to the AMOC with a regression slope of 1.0 (-1.1), an r-squared of 0.99 (0.99), significant at greater than 99% in both cases. The negative AMOC-NADW slope occurs because, when the AMOC strengthens, it results in a more positive streamfunction maximum, and the NADW transports also strengthen, resulting in more southward (negative) flow.

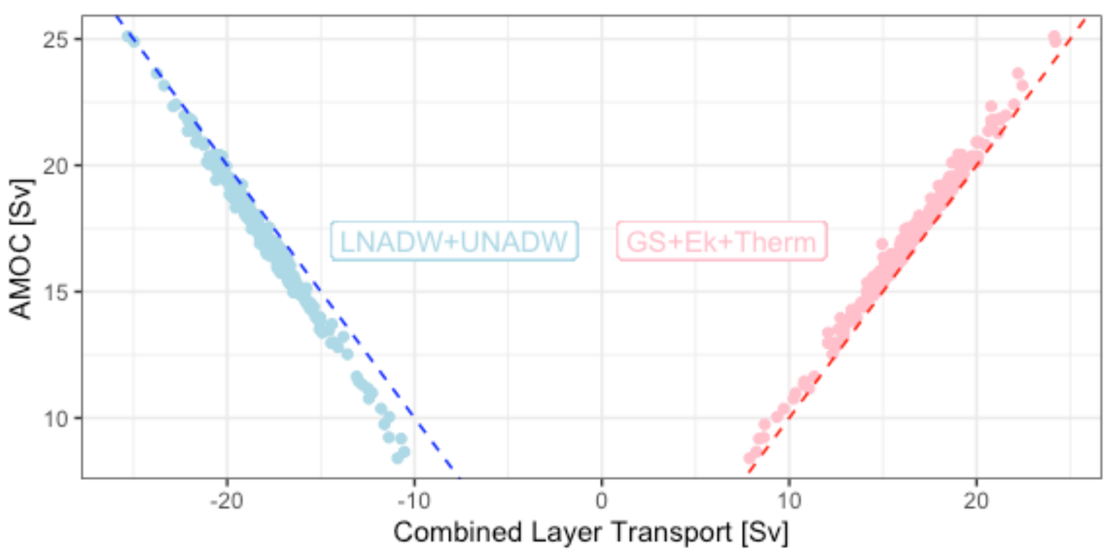

Figure 2: The relationship between the AMOC, NADW, and shallow components. The deep, cold branch is approximated by the sum of UNADW and LNADW (blue dots). The warm, shallow branch is approximated by the sum of the Gulf Stream, Ekman transport, and Thermocline transport (pink dots). Lines indicating a 1:-1 and a 1:1 relationship are shown by the blue and red dashed lines respectively. The deviations from the dashed lines are due to the exclusion of the Antarctic Bottom Water and Antarctic Intermediate Water components for the deep and shallow sums respectively.

A linear fit to the monthly, deseasonalised AMOC estimates the overall trend as -1.0 [-0.6 to -1.4] Sv/decade [10th-90th %ile] (Fig. 3), based on fitting iterated 5000 times on random selections of

50% of the datapoints. But is this decline significant? While we can categorise the statistical significance of trends, placing the climatic significance of this trend is more difficult. We cannot say that this is the signature of externally or anthropogenically forced AMOC change but we can ask when a signature of externally forced change may be detected.

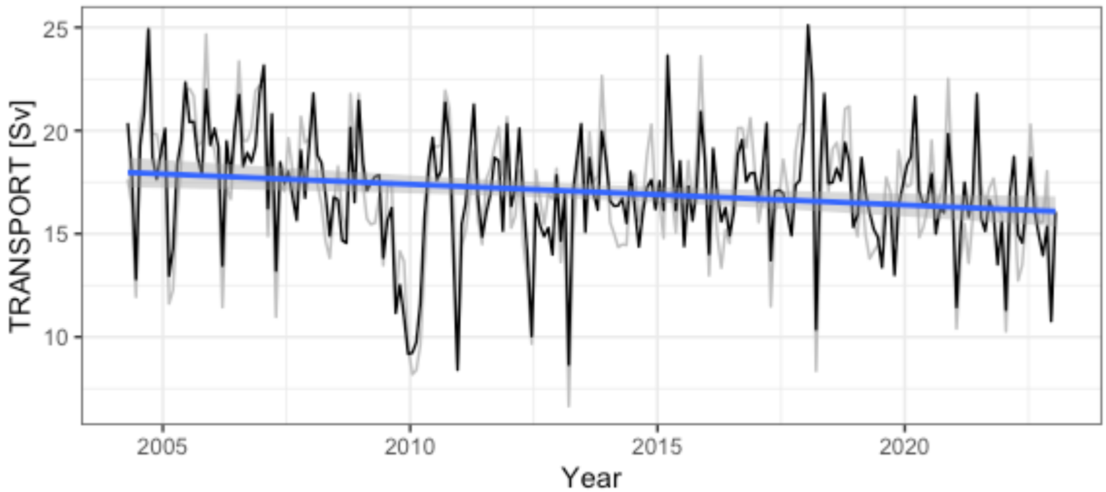

Figure 2: Linear trend in the AMOC as observed at RAPID. Linear fit (blue) to the monthly, deseasonalised values (black) is shown. Monthly values with the seasonal cycle are shown in grey.

One way of looking at the question of whether the AMOC has changed is to consider the signal-to-noise ratio. Signal-to-noise ratio has been a useful indicator of the emergence of global climate change signals in local data (Hawkins et al. 2020; Murphy et al. 2023). Here, we apply a similar methodology to investigate the emergence of low-frequency climatic oscillations and trends in the RAPID data. We define the signal-to-noise ratio based on a linear regression model:

$$y(t)=\beta x(t)+\epsilon$$

where $y(t)$ is the observed variable, such as an individual layer transport, $x(t)$ is our variable of interest, in this case the low-frequency AMOC. In this study, we use a Loess polynomial fit over 5 years to define the low-frequency AMOC. β is an unknown regression coefficient, and

$$\epsilon \sim N(0,\sigma^2),$$

where σ is the standard deviation.

There are a number of ways to consider the signal of interest. For oscillatory signals, the standard deviation of $\beta x(t)$ may be used. For emergent signals, the value of the variable of interest at a certain point may be chosen. For example, when using a signal-to-noise framework for the emergence of global temperature in local climate trends, Hawkins et al. (2020) and Murphy et al. (2023) used the end value of their variable of interest:

$$\beta x(t=t[end]),$$

in their case global mean temperature in 2018. We choose a more conservative definition based on the trend of the AMOC over the 20 years of RAPID. This allows us to define the signal as:

$$\beta m \, \Delta t,$$

where Δt is 20 years and m is the trend in variable x over the timeperiod Δt. In this case we would define the signal-to-noise ratio (SNR) as

$$SNR = signal/noise = (\beta m \, \Delta t)/\sigma,$$

where β and σ are defined as previously.

This framework lends itself to consideration of the emergence of specific trends from the noise. We can use this to define an emergence time of

$$\Delta t = (SNR \, \sigma)/(\beta m),$$

where m is a specified rate of decline. This timescale can be equated to a signal-to-noise ratio of 2 for 'unfamiliar' and to 3 for 'unknown' following (Frame et al. 2017).

In addition to the monthly, deaseasonalised data, we also consider certain components of the RAPID AMOC estimate with Ekman transport removed. Ekman transport is calculated from wind data and incorporated to the RAPID AMOC estimate directly and via a mass compensation term that ensures zero net transport across the section (McCarthy et al. 2015), which means its signal appears in the layer transports of Thermocline, AAIW, UNADW, LNADW. However, it was also found that Ekman transport impacts the deep density fields, and, by implication, the deep temperature and salinity (Frajka-Williams et al. 2016).

In terms of layer transports, UNADW, LNADW, and the AMOC estimate itself are all significantly ($p < 0.001$) correlated with Ekman transport with correlations of -0.33, -0.60, 0.68, respectively (Fig. 4). Given the lack of impact of Ekman transport change on climatic timescales (Asbjørnsen and Årthun 2023; Bryden et al. 2024), to reduce the noise in the transports, we remove the influence of Ekman transport from each layer by subtracting the regression of that layer against Ekman transport: layer_i~Ekman.

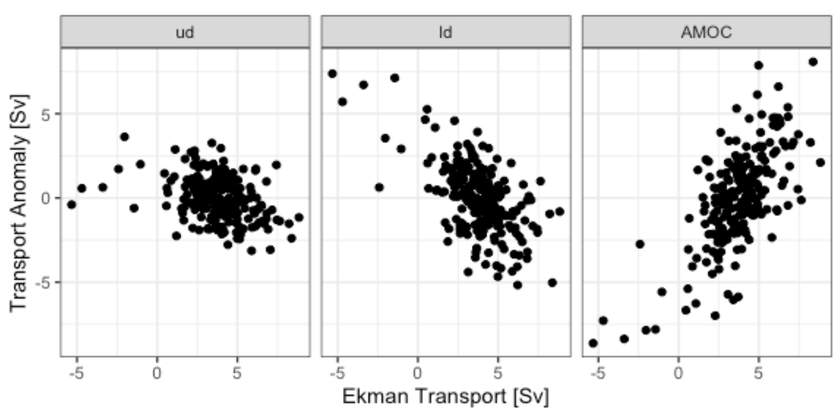

Figure 4: Components of RAPID transport with significant correlation with Ekman Transport: Upper North Atlantic Deep Water (ud), Lower North Atlantic Deep Water (ld), and the MOC.

In addition, we consider a simplified model of the LNADW transport. Worthington et al. (2021) showed that LNADW can be well described by a combination of deep density (depth = 3000 m) on the western boundary of RAPID and Ekman transport. Figure 4 (a) reproduces a version of the model of Worthington et al. (2021) for the LNADW, using deep temperature and salinity instead of density:

$$\text{LNADW} \sim \text{Ekman} + T(z=3000\text{m}) + S(z=3000\text{m}),$$

where T and S are temperature and salinity at 3000 m depth (z) on the western boundary of the RAPID array. This model fit has an R-squared value of 0.78.

We also consider this model with the influence of Ekman transport removed. We first remove the influence of Ekman transport of the LNADW, temperature and salinity via linear regression and then model the LNADW transport as:

$$\text{LNADW (no Ekman)} \sim T(\text{no Ekman}, z=3000\text{m}) + S(\text{no Ekman}, z=3000\text{m}).$$

The results of this model are shown in Fig. 4 (b). This model has an R-squared value of 0.6.

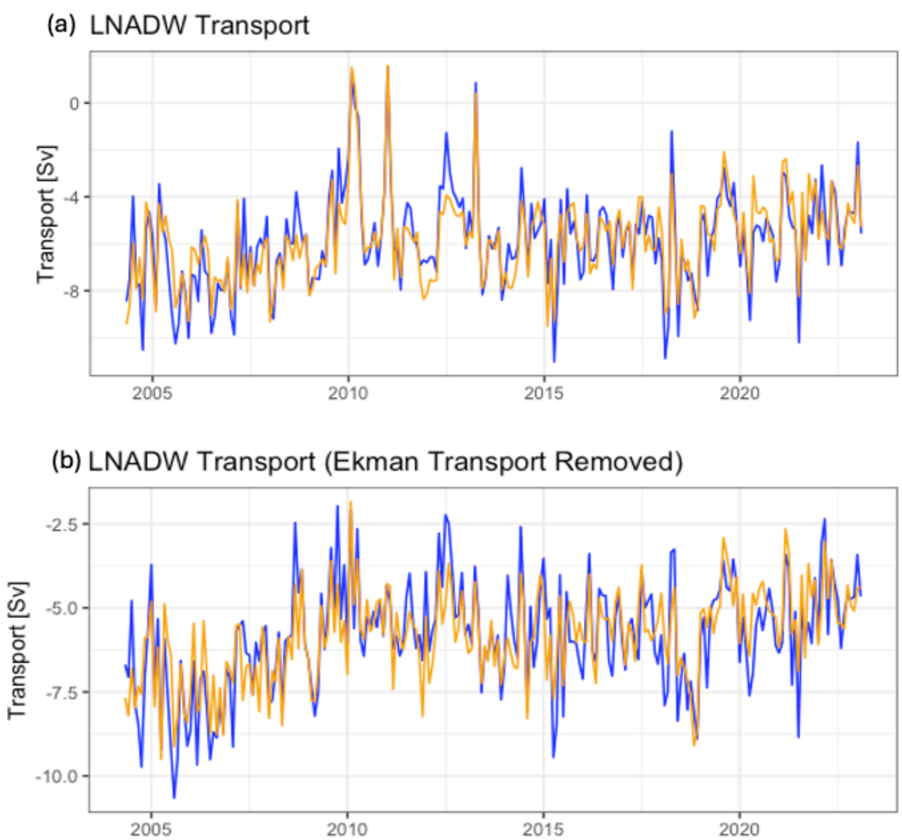

Figure 3: Models of LNADW. (a) LNADW transport (blue) and LNADW transport estimated from a linear combination of Ekman transport, temperature and salinity at 3000 m on the western boundary of the RAPID array. (b) LNADW transport with Ekman transport removed by linear regression (blue) and LNADW transport estimated from a linear combination of temperature and salinity at 3000 m on the western boundary of the RAPID array, when Ekman transport had been removed from temperature and salinity via linear regression.

Results

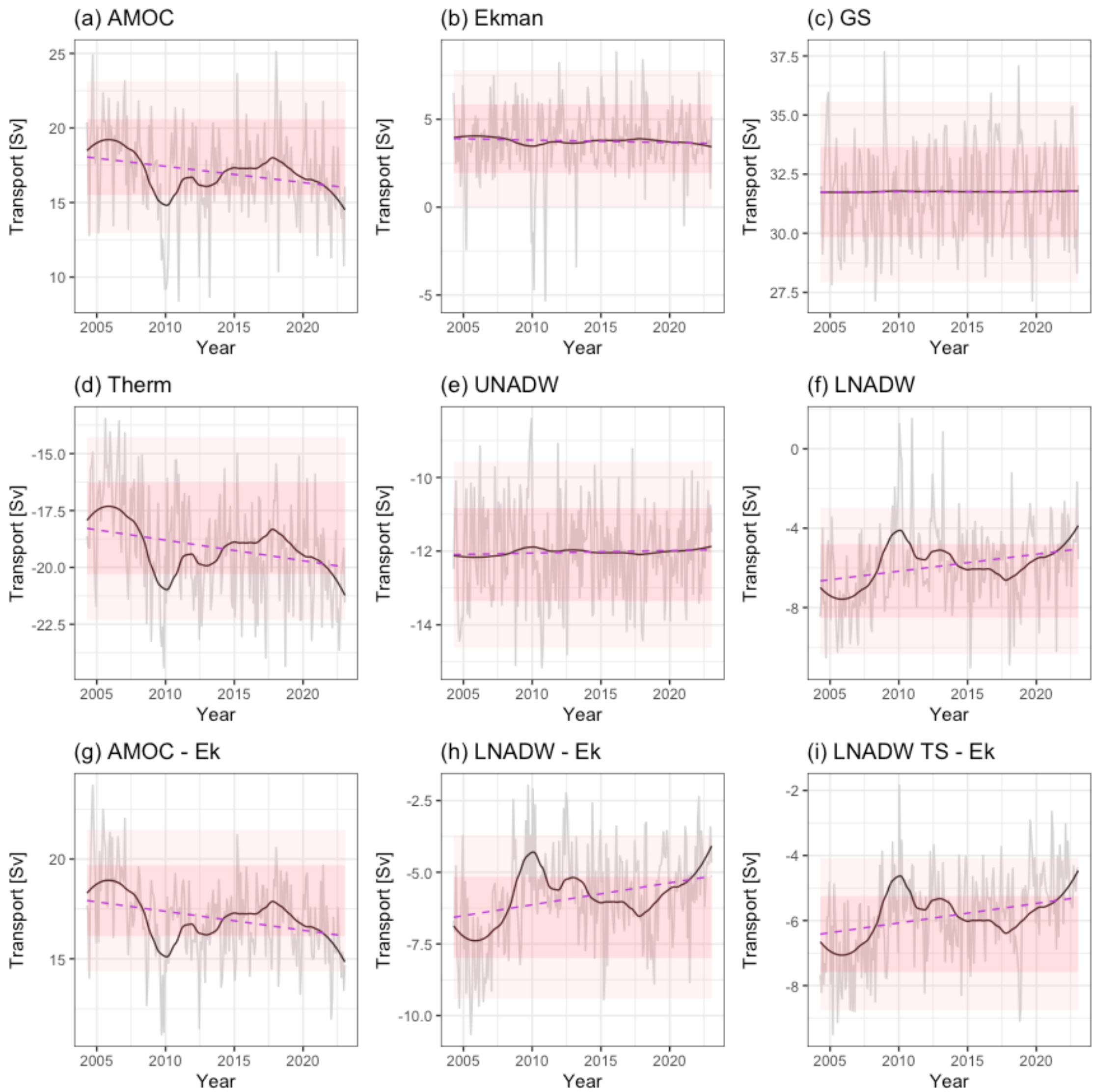

Figure 4: Signal-to-noise in components of the transport at the RAPID array at 26ºN. (a) Monthly, deseasonalised MOC estimates (grey), low-frequency AMOC signal (black) found by fitting a 5-year Loess filter, and trendline (black, dashed) estimated from linear regression iterated 500 times on 50% of the data. For each layer (b)–(f) Ekman, Gulf Stream, Thermocline, Upper and Lower North Atlantic Deep Water, the monthly, deseasonalised values (grey) were regressed against the low-frequency AMOC (black line in a), with the result shown with the black solid line. Panels (g)–(i) show the same but with the Ekman transport removed for MOC, Lower North Atlantic Deep Water, and the LNADW estimated from temperature and salinity on the western boundary at 3000 m. The light and dark pink envelopes indicate 'noise' estimates for each component at the 2 and 1 s.d. levels.

Fig. 7 shows estimation of signal and noise for the AMOC and its components in the RAPID data. The low-frequency AMOC signal (Fig. 7a), shows the decline, recovery, decline pattern and the overall decline of 1.0 [0.6-1.4] Sv/decade is shown. From 2004–2023, this overall decline only begins to emerge from the 1 s.d. envelope shown. This can be considered the 'familiar' envelope, with 'unfamiliar' emerging at 2 s.d. The reflection of this low-frequency AMOC signal is shown in the other panels of this figure. The AMOC, Thermocline, and LNADW components have low frequency signatures that emerge from the 1 s.d. envelope (Fig. 7 a, d, f). The LNADW trend is inverse relative to the AMOC i.e. when the AMOC weakens it results in less northward flow whereas when the LNADW weakens it results in less southwards flow. The Ekman, GS, and UNADW components do not emerge from the 1 s.d. envelope, reflecting these components not carrying the signature of the low-frequency AMOC (Fig. 7 b, c, e). Fig. 7 g, h, i show the effect of removal of the Ekman transport from the AMOC, LNADW, and temperature/salinity derived LNADW. Each of these variables continues to reflect the low-frequency AMOC signal but with lowered levels of noise.

The signal, noise, and signal-to-noise ratio for the AMOC and its components are shown in Table 1. The signals for each are based on the overall trend of the AMOC reflected in each component. The largest signals are for the AMOC and AMOC - Ek components of 2.04 and 1.78 Sv respectively. Thermocline and LNADW components have the next largest signals at 1.69 and 1.61 Sv respectively. Lowest signals are in the Gulf Stream, UNADW, and Ekman components. Noise levels are highest in the AMOC component, which is not surprising as it is an integrated measure of all layers together. The Ekman contribution, which has little signal (0.27 Sv) but a noise level of almost 2 Sv. Even lower signal is present in the Gulf Stream with 0.02 Sv of signal and almost 2 Sv of noise.

When signal and noise are combined, the components with the Ekman transport removed have the highest values. While signal in the AMOC component has reduced by 0.28 Sv by removing Ekman transport, the noise has decreased by 0.77 Sv or 30%, increasing the signal-to-noise ratio to 1.0. Improvements to the signal-to-noise ratio are also evident in both LNADW components. The noise component for the LNADW dropped by 0.42 Sv or 22% to 1.42 Sv when Ekman transport is removed. The LNADW TS estimate shows a lower signal of 1.13 Sv but also lower noise of 1.17 Sv, giving a signal-to-noise ratio of 1.01. Given that this model is simply based on temperature and salinity at a single point on the western boundary of 26ºN at 3000 m depth, our results reflect how much of the low-frequency AMOC signal is present in the deep western hydrography.

Considering the components that have not had Ekman transport removed, the LNADW component has a higher signal-to-noise ration that the AMOC, which indicates that these deep transports may be better at detecting the climatic AMOC. Other components have much lower signal-to-noise ratios. The thermocline component, which estimates the southward flow in the upper 1000 m of the ocean, was the component that the decline in the first 8 years of RAPID was mainly attributed to. It has a signal-to-noise ratio of 0.84. All the other components (Gulf Stream, UNADW, and the aforementioned Ekman transport) have signal-to-noise ratios of less than 0.15.

Overall, the signal-to-noise ratio for all components considered in Table 1 is low and noise swamps the low-frequency AMOC signal. The maximum signal-to-noise ratio values are also lower than the ‘unfamiliar’ (SNR > 2) or ‘unknown’ (SNR > 3) thresholds (Frame et al. 2017).

Each of these layer transports has a scaling factor (β) to the AMOC itself. Estimates of the AMOC itself are by definition close to 1. Deviations from 1 are due to either the removal of Ekman transport or skews in the relationship of the monthly to the low-frequency AMOC data. Negative scale factors are shown for lower and upper North Atlantic Deep Water due to the fact that a weakening in AMOC is less northward transport is reflected in these layers as less southward transport. There is also a dilution of the AMOC signal in certain components. The LNADW based on temperature and salinity with Ekman transport removed has a scale factor of -0.59, showing that trends in this layer are almost half those of the low-frequency AMOC.

We can use these values to estimate when the current trend of 1.0 Sv/decade would result in values that are either unfamiliar or unknown in the definition of Frame et al. (2017). The components with the Ekman transport removed would hit unfamiliar (unknown) around the 2040s (2060s). Not reducing the noise by removing Ekman transport pushes this threshold back by approximately 5 (10) years.

Table 1: Signal and noise components for MOC, its layer transports, and certain transports with Ekman removed.

	Signal [Sv]	Noise [Sv]	S to N Ratio	Scale Factor	Unfamiliar [Year]	Unknown [Year]
LNADW - Ek	1.43	1.42	1.01	-0.75	2042	2060
AMOC - Ek	1.78	1.77	1.00	0.93	2042	2061
LNADW TS - Ek	1.13	1.17	0.96	-0.59	2043	2063
LNADW	1.61	1.84	0.87	-0.84	2048	2070
Therm	1.69	2.01	0.84	0.89	2049	2072
AMOC	2.04	2.54	0.80	1.07	2051	2075
Ekman	0.27	1.94	0.14	0.14	2280	2418
UNADW	0.13	1.26	0.10	-0.07	2377	2564
GS	0.02	1.90	0.01	-0.01	4931	6395

Discussion

In this paper, we have considered the observed AMOC change in a signal-to-noise framework. The AMOC, as observed by the RAPID array, can be considered with its component parts including Ekman transport, Gulf Stream and thermocline transport, upper and lower North Atlantic Deepwater. Low-frequency variability or multi-year variability has been discussed in the RAPID observations by Smeed et al. (2014), who reported an AMOC decline in the 8 years from 2004, and (Moat et al. 2020), who reported a stronger AMOC from 2014–2018 than previously. In this latest release of the RAPID data to January 2022, the AMOC has weakened steadily since late 2017 (Fig. 3). Given the context of multi-year reversals in AMOC trends since the beginning of RAPID observations in 2004, the first explanation for this latest downturn is likely to be natural Atlantic multi-year variability (Roberts et al. 2014).

We have considered what would be a notable change in AMOC using the language of 'signal' and 'noise' following similar studies of climate data e.g. (Hawkins et al. 2020; Murphy et al. 2023). In this context, we estimate noise as the standard deviations of residuals from a low-frequency AMOC signal, using the language of 'unfamiliar' and 'unknown' for signals that are 2 and 3 standard deviations from a baseline respectively. In comparison with these studies, of the emergence of global temperature trends in local observations, there are a number of very different challenges for the AMOC.

Firstly, the definition of the 'signal' is not straight forward. A choice must be made about the level of smoothing applied to data. We have used a 5 year Loess polynomial fitted to the AMOC data as an estimate of low frequency variations and define this as our signal. This is a longer smoothing interval than that used by Smeed et al. (2018) of 2 years. We repeated our analysis with multiple smoothing intervals. Shorter intervals produce more variabile results but increasing the smoothing interval to 10 years yields qualitatively similar results to the 5 year window. To calculate the final value for the emergent signal, we choose the value of the linear trend in the AMOC over a 20 year period beginning at the start of RAPID in 2004.

Secondly, choosing a baseline or starting point is far more challenging. Studies of global temperature can employ standard definitions of pre- or early-industrial period of 1850–1900. The same is not possible for AMOC which does not have direct, continuous observations prior to the 21st century. In this study, we have considered a starting point based on linear fit to signal. The period of 2004–2008 was shown by (Smeed et al. 2018) to have had a significantly stronger AMOC than the period 2008–2017 so simply choosing an initial year or few years, leads to a potential high bias. Despite the subsequent recovery of the AMOC (Moat et al., 2020), our results show values of AMOC and LNADW reaching weak points in January 2023—the end of the RAPID timeseries at time of writing. The more conservative baseline of beginning of a linear trend was chosen to address the question: if the AMOC does decline due to climate change, when can we start to see this in observations?

Results highlight the lack of signal and high noise in the Ekman transport and motivated the removal of the fingerprint of Ekman transport from correlated variables. This was successful and significantly reduced the noise, thus improving variables' utility for detecting climatic change. The question could be asked whether more signal may appear in the Ekman component in the future due to changing wind patterns, potentially linked to climate change. This is not supported by climate model analysis and studies have shown that Ekman transports contributes little to future AMOC decline (Asbjørnsen and Årthun 2023; Bryden et al. 2024). This is not to say that wind will have no effect on future AMOC, as changes may well manifest in wind-driven components such as the Gulf Stream.

Results highlight the lack of signal and high noise in the Gulf Stream components also.The Gulf Stream in the RAPID calculation is estimated by the Florida Current timeseries and the lack of AMOC signal has been increased since the revision of these estimates by Volkov et al. 2024. So why don't we regress out the Gulf Stream in the same manner as Ekman transport? Firstly, the Gulf Stream was not seen to covary with the other components as strongly as the Ekman transport. Secondly, long term studies such as Asbjørnsen and Årthun 2023; and Bryden et al. 2024 have shown that there is a significant contribution of the Gulf Stream to AMOC decline in climate models. Nonetheless, the lack of signal raises the question of how reconstructions of the Gulf Stream such as Piecuch et al. 2020 can be interpreted in an AMOC context.

The manifestation of low-frequency AMOC change in AMOC components may seem obvious: the components sum to give the AMOC strength and so there must be a relationship. It is therefore surprising perhaps that the Florida Current and UNADW showed little of this low-frequency AMOC signal. LNADW proved a sensitive indicator of low-frequency AMOC change. Using the simple model derived from Worthington et al. (2021), we were able to recover much of the low-frequency AMOC signal in the deep temperature and salinity at the western boundary. This is a powerful result: the full AMOC estimate require multiple moorings across the Atlantic; this deep temperature and salinity are derived from a single location. This shows the importance of deep hydrographic properties in understanding and detecting AMOC change. While a powerful result, it is perhaps not a surprising one: deep density was highlighted as a sensitive indicator of AMOC change by Baehr et al. (2007) in a modelling study shortly after RAPID began.

The utility of deep hydrography in the detection of AMOC change does come with a caveat that, in our analysis, the AMOC signal is diluted when looking at its manifestation in the LNADW by a factor of 0.75 in the full LNADW transports and by 0.59 in the LNADW based on deep temperature and salinity (Ekman removed in both cases). This poses a challenge as a climatic AMOC signal may be small. For example, assuming the Atlantic multidecadal variability in sea surface temperatures is linked to the AMOC, combined with the scaling of 4 Sv/ºC relation between AMOC and Atlantic SSTs from Caesar et al. (2018), the signal would be 0.5ºC over 2 decades or a 1 Sv signal. This is already close to the limits of hydrographic accuracy. McCarthy et al. (2015) showed that the absolute accuracy of 0.8 Sv (0.6 Sv) for the 10-day (annual) AMOC estimates. Our simple model of LNADW based on temperature and salinity here shows a similar sensitivity. Temperature changes of 0.03ºC or salinity changes of 0.004 at 3000 m on the western boundary are sufficient to change the estimate of LNADW by 1 Sv. This poses a real challenge, in particular, for salinity calibration as the target accuracy for salinity is 0.003 (temperature calibration has a target accuracy of 0.002ºC). This poses a challenge for detection of changes in our current framework and also for extension of our methodology back in time when salinity calibration is even less robust.

We asked a question at the start of this manuscript of whether the 1.0 Sv/decade weakening trend in the RAPID AMOC was significant, which in the language of signal and noise, would be better framed as asking whether the weakening resulted in 'unfamiliar' or 'unknown' AMOC levels. The answer to both is 'no'. We have shown that even in the sensitive estimators of AMOC change—AMOC and LNADW with Ekman noise removed—'unfamiliar' ('unknown') levels won't be reached by this trend, if it continues, until around the 2030s (2060s). The framework of signal and noise also allows us to consider when larger trends, were they to occur, would emerge from the noise. For example, the trend in AMOC since 2018 has followed a 5 Sv/year weakening trajectory. This rate of decline is consistent with the mid-21st century collapse of the AMOC discussed by Ditlevsen and Ditlevsen (2023). Were this to continue, unfamiliar values of AMOC would emerge in around 4 years, given an estimated noise level of 2 Sv in AMOC values when seasonality and Ekman influence is removed. In other words, if this extreme scenario were to occur, RAPID would detect it by the end of the decade.

Conclusions

We have considered observed AMOC change at the RAPID array in a signal-to-noise framework and conclude that we have yet to see AMOC values that are 'unfamiliar' or much less 'unknown'. We have explored the sensitivity of observations in the RAPID array to detection of signals and emphasise the importance of removing those components that carry much noise and little signal such as Ekman transport. In our framework, the overall trend from RAPID of 1.0 Sv/decade, which is close to the estimate of future AMOC weakening from climate models (Weijer et al., 2020), will result in unfamiliar values by the 2040s and unknown values by the 2060s.

Our confidence in these future climate projections is typically based on a climate model's ability to reproduce the past—something that climate models are not so good at for AMOC (McCarthy and Caesar 2023)—and that past AMOC strength is a controversial topic in its own right (Caesar et al. 2021; Kilbourne et al. 2022). Whether or not the AMOC has been declining overall since the mid-20th century depends heavily on whether or not the AMOC was stronger in the first half of the 20th century (Caesar et al. 2021). In this study, we have highlighted the potential for deep hydrography, near the western boundary of the Atlantic to provide a sensitive estimate of low-frequency AMOC variations and offers the potential to reconstruct the AMOC in the past, although challenges around calibration remain.

Nonetheless, the challenge in detecting climatic change in the AMOC is large. The noise is large and the signal may be small. This emphasizes the importance of high quality direct observations of the AMOC such as those provided by RAPID since 2004, not only as a tool for monitoring the AMOC in the present but also for understanding the past and contextualising future changes.

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