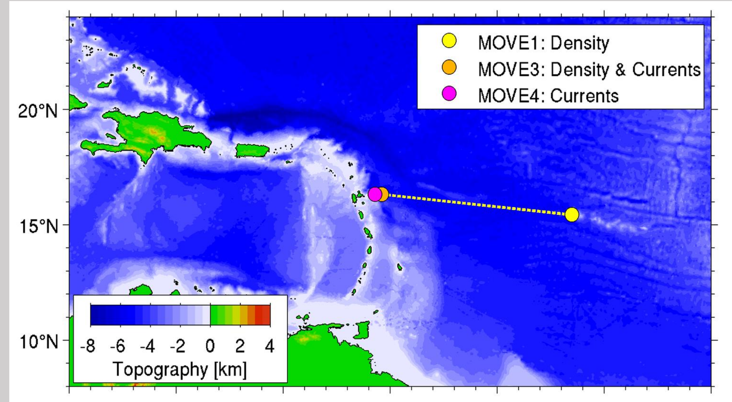
Southward NADW transport and property changes at 16°N

Jannes Koelling[1], Matthias Lankhorst[1], Uwe Send[1], Rolf Käse[2] and Nuno Serra[2]

[1] Scripps Institution of Oceanography, University of California San Diego, USA
[2] Institute of Oceanography, CEN, University of Hamburg, Germany

The MOVE project

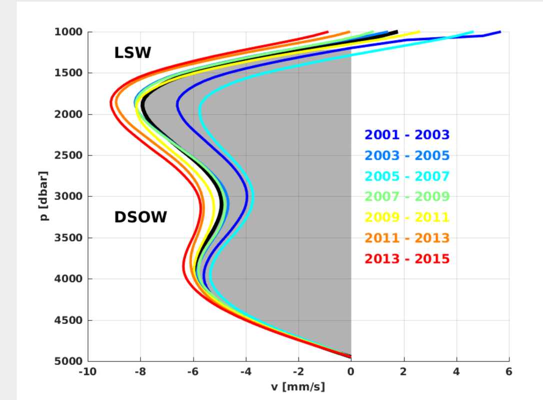
The MOVE (Meridional Overturning Variability Experiment) observational setup consists of two endpoint moorings measuring density at the edges of an approximately rectangular section along 16°N in the tropical Atlantic, between Guadeloupe and the Mid-Atlantic ridge (MAR), used to calculate the geostrophic flow of North Atlantic Deep Water (NADW) through the section. Current meters are used to measure the flow over the Western boundary wedge. Bottom pressure recorders have been deployed alongside the MOVE 1 and MOVE 3 moorings at the boundaries in most years.
The moorings have been deployed in consecutive 1- or 2-year deployments since 2000, providing a 17-year time series of bottom-referenced NADW transport.

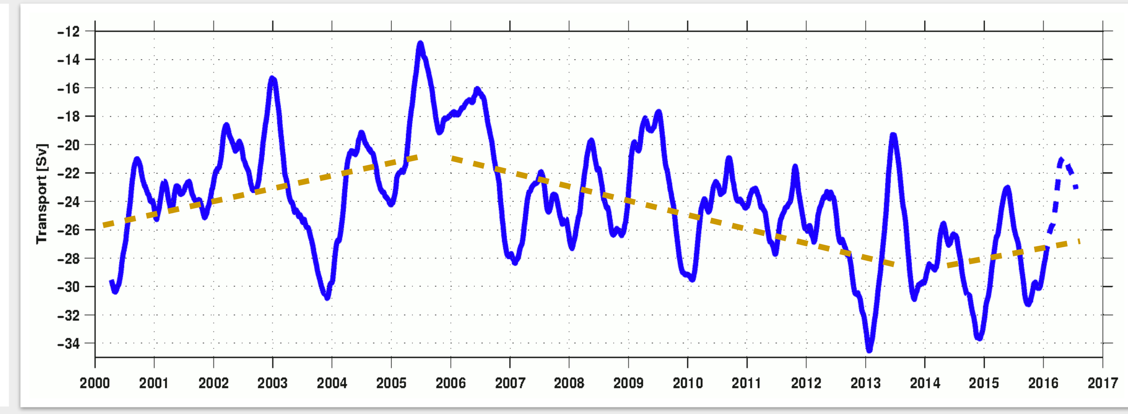


Current MOVE setup (from Send et al., 2011)

NADW transport through the MOVE section

The geostrophic transport between the MOVE3 and MOVE1 moorings is calculated from the thermal wind equations, integrating the velocity shear upward from v = 0 at 4950 dbar to obtain the velocity profile at each time step, which is then integrated between 1200 and 4950 dbar to calculate the transport perpendicular to the section. The reference level is chosen because it represents the approximate depth of the zero crossing between southward flowing NADW and northward flowing AABW, and little variability is expected at these depths on long time scales *(Send et al., 2011).* Two distinct maxima are visible in the mean velocity profile, associated with the two main water masses of the NADW, Labrador Sea Water (LSW) and Denmark Strait Overflow Water (DSOW).
The current 17-year transport time series exhibits decadal variability, indicated by the dashed lines in the figure. Velocity profiles show a strengthening of both the LSW and the DSOW core in recent years relative to the beginning of the record.

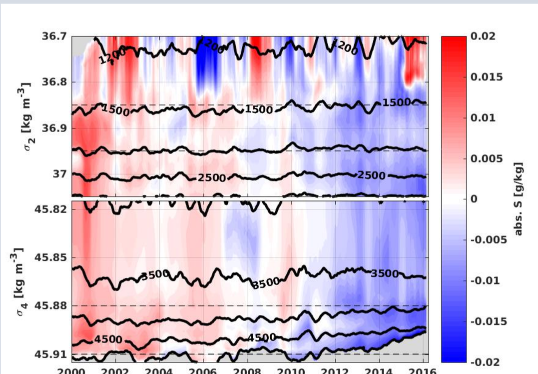


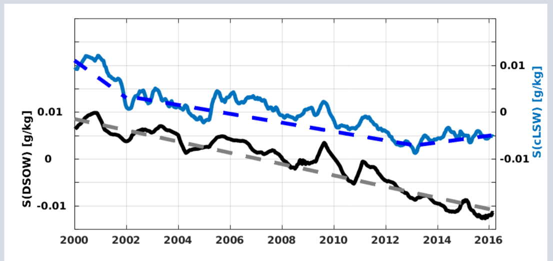


Left: 17-year Mean geostrophic velocity between M1 and M3 (black), with the depth range used in the transport calculation shaded gray, and 2-year means (colors)
***Right**: Bottom-referenced NADW transport through the MOVE section, updated from Send et al. (2011); yellow dashed lines show approximate decadal variability*

Western boundary water mass changes

The 17-year observational record collected as part of MOVE shows distinct patterns of variability in several of the main NADW water masses:

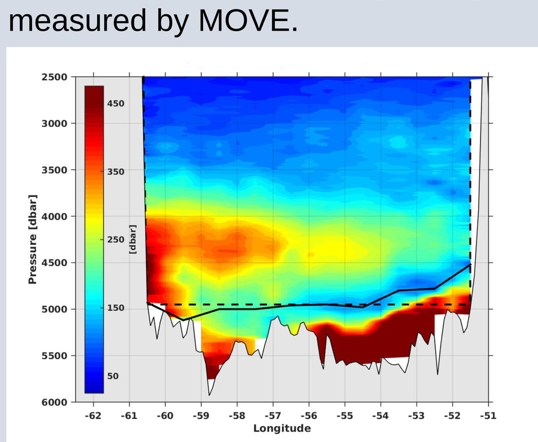


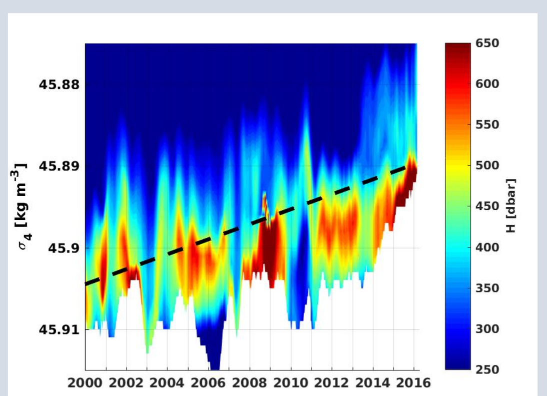


***Right:** Salinity anomaly averaged over the cLSW ($36.85 \leq \sigma_2 \leq 36.95\ \mathrm{kg\,m^{-3}}$) and DSOW ($45.88 \leq \sigma_4 \leq 45.91\ \mathrm{kg\,m^{-3}}$) layers*

***Left:** Salinity anomaly on isopycnals, with depths shown as black contours*

Salinity in NADW below about 1500m, or the 36.85 σ_2 isopycnal, at the Western boundary has decreased throughout the MOVE record. Variability in the cLSW layer is characterized by a sharp decrease of almost 0.01 g/kg around 2001, followed by a more gradual freshening over the next decade. The decrease in 2001 coincides with the arrival of the 1987-94 class of LSW at 16ºN inferred from CFC concentrations *(Rhein et al., 2004)*, suggesting a 5 year transit time from the Abaco line at 26.5ºN, where a similar strong initial drop and sustained slower decrease of S in this layer was observed after 1996 *(van Sebille et al., 2011)*. Salinity starts to increase again in 2013, which could mark the beginning of a period of increasing salinity similar to that observed at Line W since 2005 *(Le Bras, 2017)*.
The freshening in the DSOW layer is approximately linear throughout the record, with S decreasing by about 0.02g/kg between 2000 and 2016. This trend is consistent with changes in the source region, where Dickson et al. (2002) reported a freshening of 12ppm/decade between the 1970s and 2000, shown as a gray dashed line in the above figure.
The DSOW core can be identified as a maximum in layer thickness (≈ minimum PV). Hydrography data reveals a strong core at the Western boundary, with a tongue extending into the interior centered at 4250dbar, consistent with the velocity maximum.
Tracing the core in density space at the Western boundary mooring reveals that DSOW core density decreases over time, as the observed freshening is only partially compensated by temperature changes. The resulting change in density shear is responsible for the strengthening in the bottom-referenced DSOW velocity in recent years *(top right panel),* i.e. an increase of the deep maximum of southward NADW flow relative to the maximum northward flow of Antarctic Bottom Water (AABW) below, which lies outside the range measured by MOVE.





***Left:** Layer thickness (vertical distance between σ_4 isopycnals spaced 0.01 $\mathrm{kg\,m^{-3}}$ apart) along the MOVE section, averaged over 5 hydrographic cruises between 2000 and 2005. The dashed line shows MOVE coverage, and the solid line corresponds to the AABW/DSOW interface*
***Right:** Layer thickness in the DSOW density range. The dashed line shows the change in DSOW core density caused by the Dickson et al. salinity trend with constant temperature. Note different color scales in left and right figures*

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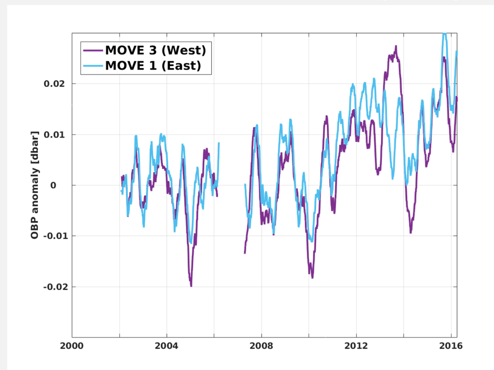
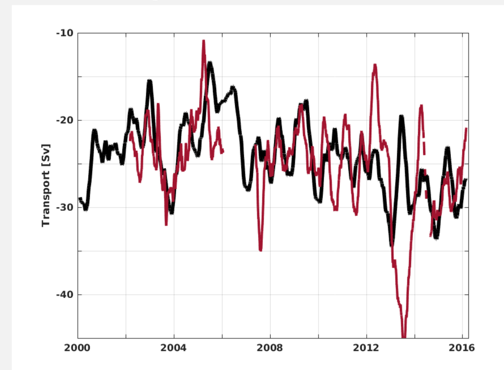
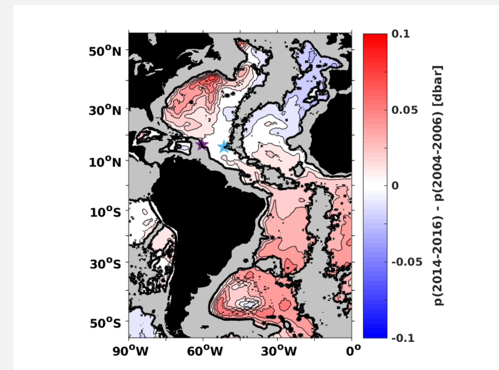
Bottom pressure Variability

A key goal for the MOVE array going forward is to investigate the changes in velocity at the reference level, or, equivalently, the barotropic component of the flow, to validate decadal trends in the bottom-referenced transport estimates. As the MOVE moorings only span the Western half of the Atlantic basin, an estimate of barotropic flow through mass conservation constraints as used in the RAPID array *(McCarthy et al., 2015)* is not possible. To ascertain whether changes in the bottom-referenced transport estimates *(see top right panel)* correspond to real variability, the change in the reference level velocity needs to be resolved, which can be achieved by measuring pressure changes at both endpoints.
Although Bottom pressure is measured *in situ* at the MOVE sites, the strong instrument drift that pressure recorders suffer from makes them unsuitable for measuring decadal trends in the reference level velocity *(Watts & Kontoyiannis, 1990)*. This can be mitigated by using data from the GRACE satellite mission, which measures ocean mass as gravity anomalies, together with the ocean-based measurements.







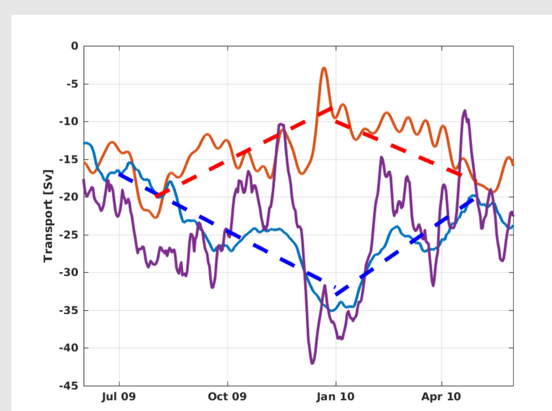
***Left:** Bottom pressure changes at MOVE 3 from a combination of in situ and GRACE JPL Mascon data (Watkins et al., 2015)*
***Center:** MOVE transports relative to zero bottom flow (black) and relative to OBP-derived ref. level velocity (red)*
***Right:** Change in bottom pressure between 2004-06 and 2014-16 in GRACE CSR Mascon data (Save et al., 2016); colored symbols show locations of the MOVE moorings*

To combine the high temporal resolution *in situ* data of bottom pressure with information on changes on long time scales from GRACE, the exponential + linear fit used to remove instrument drift is adjusted to incorporate long-term trends from the satellite data, seen in the figure above as the increase in bottom pressure occurring at both sites after 2010. Applying the reference level velocity derived from these measurements to our transport estimates does not qualitatively change the decadal variability evident in the transport calculated from density measurements alone. While this result would validate the assumption of negligible variability at the reference level on long time scales, there is still uncertainty about the veracity of long-term trends in the GRACE data used here, which will need to be resolved to obtain a reliable estimate of this deep variability.
The GRACE data exhibit a pattern of increasing ocean mass over the last decade, which appears to follow the approximate spreading pathways of NADW and AABW. The timing of the mass increase along the path of NADW is similar to that seen in the bottom pressure time series at MOVE, suggesting a wave-like adjustment rather than advective propagation of anomalies. This spatial pattern associated with decadal changes in ocean mass lends some credence to the observed changes on long time scales, as spurious trends that can result from the data processing, such as those associated with the geocenter or glacial isostatic adjustment (GIA, *Chambers et al., 2010)*, would not be expected to follow patterns of real oceanic variability

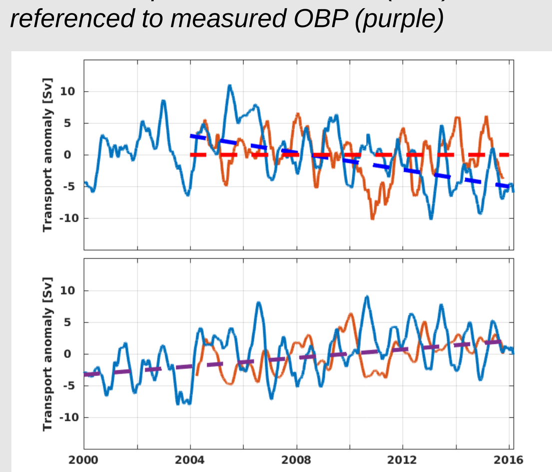
Comparison with 26°N

MOVE is one of two long-term observational mooring arrays designed to measure the southward NADW transport in the North Atlantic comprising both boundary and interior pathways. The RAPID array measures all components of the AMOC across the entire basin at 26ºN, including the southward NADW flow *(McCarthy et al., 2015)*. RAPID and MOVE exhibit opposing signals during strong "events" on short timescales, which can be validated using the bottom pressure data.

On long time scales, water mass changes and dynamic height anomalies at the Western boundary are generally consistent between RAPID and MOVE *(Frajka-Williams et al. 2017, see also talk by M. Lankhorst at this conference),* but trends disagree, with MOVE showing an increase of transport over the last 10 years, while RAPID reports a decreasing trend. The methods used at the two sites are different, as RAPID measures transport across the entire width of the basin, and uses mass conservation to infer the reference level velocity. However, differences persist even when calculating transport at RAPID in a similar fashion to MOVE, referencing to 0 at the bottom and integrating only from the Western boundary to the MAR, implying that the discrepancy in decadal variability can not entirely be explained by the methodology.
The trend in bottom-referenced Western basin transports between 2004 and 2016 at the two sites is consistent when replacing the time-varying density measurements at the Western boundary with a time-mean profile, i.e. using only variability from the moorings at the western edge of the MAR. This suggests that, despite similar water mass changes at the two latitudes, differences at the Western boundary are partially responsible for the diverging decadal trends.



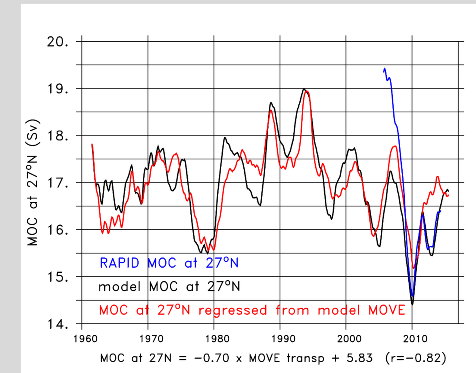
1-year segment of RAPID transport (red) and MOVE transport referenced to 0 (blue) and referenced to measured OBP (purple)

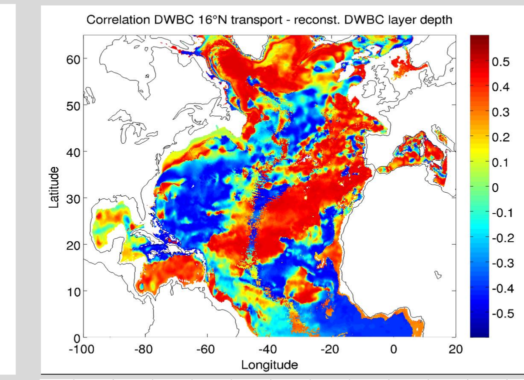


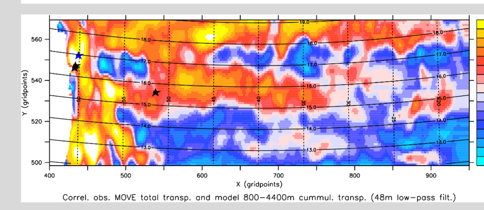
***Top panel:** Geostrophic bottom ref. transport anomalies between RAPID West and MARwest (red) and MOVE3 and MOVE1 (blue)*
***Bottom panel:** Same as above, but using a time-mean profile for the Western boundary mooring*

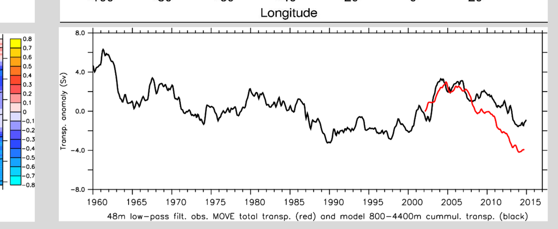
Numerical simulations

To put observations at MOVE into a broader context, we use output from a 60-year run of a high-resolution numerical model *(Serra et al., 2010).* Transport measured with a MOVE-like setup over the 60-year model run compares well with the overturning on long time scales, suggesting that our method can be used to monitor decadal to multi-decadal AMOC variability.
The best agreement of model NADW transport with observational results is found when integrating over a narrow region close to the Western boundary between 800-4400m, owing to differences in basin geometry in the model. The transport calculated over this region shows decadal trends consistent with observations.
A singular value decomposition of LSW layer thickness reveals large scale patterns correlated with transports at the MOVE latitude, aligned along the SW-NE direction, which is characteristic of planetary Rossby waves.



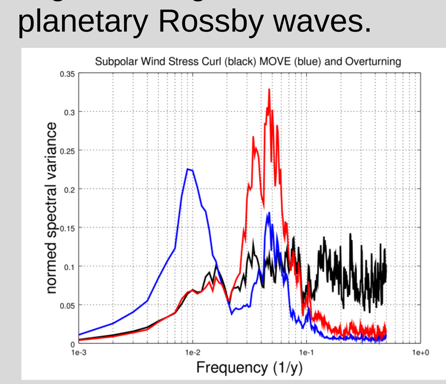


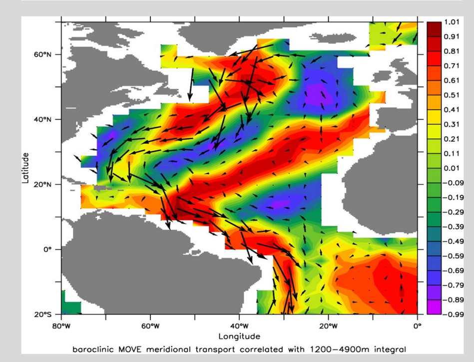




***Top Left:** Transports over MOVE section in the model regressed on 27N AMOC*
***Top Right:** Correlation between 16ºN transport and two of the leading modes of LSW thickness ($40.9 \leq \sigma_3 \leq 41.49$) from a singular value decomposition*
***Bottom left:** Correlation of model transport integrated eastward from the western boundary with observational MOVE data*
***Bottom right:** time series of transport between Western boundary and point with maximum correlation (blue symbol in bottom left plot), compared with observational data*

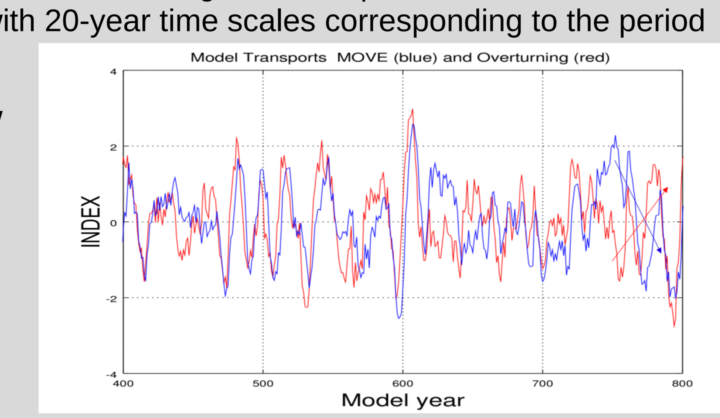
A 2000-year run of a coupled ocean-atmosphere model *(Köller et al., 2010)* gives insight on variability occuring on even longer time scales, far exceeding the current observational record. Power spectra of overturning and NADW transport at the approximate MOVE location show enhanced variability on 20-year time scales, with an additional peak at 100-year time scales for MOVE. Regions of maximum correlation of vertically averaged v with MOVE transports are again oriented in a SW-to-NE direction indicative of Rossby waves. These results suggest energy being transferred from wind forcing in the subpolar North Atlantic to these longer time scales through stochastic resonance, with 20-year time scales corresponding to the period of basinwide Rossby waves in the North Atlantic.





***Top:** Power spectra of SPNA wind stress curl, MOVE transports and MOC in a 2000-year model run*
***Bottom:** Correlation of transport at MOVE with depth averaged v at each point*

While data from the 2000 year numerical simulation show generally in-phase behavior of the MOC at 27ºN and MOVE-like NADW transport, they also contain periods of several decades with opposing variability in the two time series. Such out of phase behavior between 16ºN NADW transport and 27ºN AMOC shows that differences in decadal variability like those between MOVE and RAPID may persist for extended periods of time within a longer record marked by mostly coherent changes.



400-year segment of model overturning at 27º N(red) and NADW transport at MOVE (blue); arrows show period with opposing trends

Main points:

- Baroclinic (bottom-referenced) NADW transport at MOVE shows decadal variability, with multi-year periods of increasing and decreasing flow through the section
- Properties of the main water masses making up NADW are changing over time, generally moving towards lower salinity
  - DSOW salinity steadily decreases at a rate consistent with changes in the source region
  - LSW salinity drops strongly between 2000 and 2002 due to the arrival of 1987-94 LSW, and decreases more gradually afterwards; a slight increase is evident since 2013, and may mark the beginning of a return towards higher salinity
- Resolving the reference level velocity is a crucial step towards validating transport estimates at MOVE, but a robust method to measure it remains elusive; bottom pressure data show only a weak trend on long time scales, but there may be spurious trends in the GRACE data used
- MOVE transport variability differs from that at the other prominent mooring array measuring NADW flow, RAPID; bottom pressure data validate the transport divergence occurring on short time scales; differences in decadal trends persist when calculating a "MOVE-like" transport at 26ºN, and appear to at least partially emanate from the Western boundary
- Model data show that the MOVE method resolves MOC variability, and suggest that planetary Rossby waves are responsible for the multi-decadal variability in the MOC and in NADW transport; a 2000-year model run contains multi-decade periods with opposing trends in 16ºN NADW transport and 27ºN MOC, similar to observations

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