

Opposing decadal changes for the North Atlantic meridional overturning circulation

M. Susan Lozier^{1*}, Vassil Roussenov², Mark S. C. Reed¹ and Richard G. Williams^{2*}

The hydrographic properties of the North Atlantic Ocean changed significantly from 1950 to 2000: the subtropics warmed and became more saline, whereas the subpolar ocean cooled and freshened. These changes directly affect the storage of heat and fresh water in the ocean, but their consequences for ocean dynamics are determined by the resultant changes in seawater density. Here we use historical hydrographic data to show that the overall seawater density in the North Atlantic basin decreased during this 50-year period. As a result of these density changes, sea-surface heights changed in a spatially varying pattern with typical rates of 2 mm yr^{-1} , in broad agreement with tide-gauge measurements. Melding the observed density fields within a numerical model we find a slight weakening in the overturning of the subtropical gyre by $-1.5 \pm 1 \text{ Sv}$ and a slight strengthening in the overturning of the subpolar gyre by $+0.8 \pm 0.5 \text{ Sv}$. These gyre-specific changes run counter to the canonical notion of a single, basin-scale overturning cell and probably reflect interannual and decadal trends rather than any long-term climate trend. We conclude that gyre dynamics strongly affect temperature and salinity changes that translate into changes in the meridional overturning circulation.

The importance of the ocean in our climate system has been highlighted by recent studies illustrating its capacity as a heat, freshwater and carbon reservoir. In particular, the deep ocean has been shown to be a reservoir for anthropogenic carbon dioxide¹, with the deep limb of the meridional overturning circulation (MOC) apparently responsible for ventilating the deep waters with this tracer. The capacity for the deep ocean to continue to act as a reservoir for heat and carbon is critically dependent on this overturning circulation. As studies have revealed the warming of the global ocean's waters^{2,3} and freshening at high latitudes^{4–6}, concern has mounted that these property changes are impacting the ocean's density field such that the MOC might slow^{7,8}, though the timing of this reduction remains unclear.

Measurements from the UK RAPID array along 26.5° N since 2004 are providing current estimates of the MOC (ref. 9), yet assessments of the long-term behaviour of the MOC remain elusive. Continuous time series from the RAPID array have shown that intra-annual variability of the MOC swamps interannual variability at this latitude, thus estimates of MOC change on the basis of synoptic surveys separated by years and decades^{10,11} are unlikely to represent a realistic long-term trend. Unfortunately, modelling studies focused on temporal changes in the MOC in the North Atlantic have, so far, formed no consensus on either the magnitude or the sign of MOC changes in the North Atlantic¹². Further confounding an assessment of past MOC changes, recent modelling studies have called into question the canonical picture of a single, basin-scale, overturning cell in the North Atlantic^{13–15}. Results from these modelling experiments, which yield gyre-specific MOC changes, resonate with a past study of historical hydrographic data that showed pronounced gyre-specific changes in the North Atlantic property fields from 1950 to 2000 (ref. 16). Collectively, these studies suggest that an assessment of the North Atlantic MOC should consider latitudinal variations within the basin and that an inquiry into the linkage between gyre-specific property changes and MOC changes is warranted.

Towards this end, we estimate past changes in the MOC by using all hydrographic data collected from 1950 to 2000 over the entire North Atlantic basin. We are interested in identifying the spatial and temporal pattern of density change in this basin, the relative contribution of temperature and salinity to this change, and, importantly, the basin-wide MOC pattern that is dynamically consistent with these changes. Owing to uncertainties with the calculation of the MOC from the density field alone, we carry out this calculation within the context of a dynamical model to ensure that the velocity fields are dynamically consistent. Our goal with this study is to expand the spatial and temporal domain of past MOC estimates to provide a broader context for the interpretation of modelling and observational estimates of overturning in the North Atlantic.

North Atlantic property changes

For this investigation, we use historical hydrographic station data (pressure, salinity and temperature) collected between 1950 and 2000 (refs 17,18; Fig. 1a). Relatively sparse hydrographic data before the 1950s, and the sizeable temporal lag in the reporting and recording of more recent data, effectively dictates this temporal domain. The constraints imposed by data density—even in this most measured basin—limit our analyses of property changes over the past 50 years to two options: first, we sacrifice spatial resolution to analyse time series (from 1950 to 2000) of property changes averaged over the central subtropical and subpolar basins (Fig. 1a); second, we maintain the spatial resolution of the data and restrict our analysis of temporal change to two time periods, as explained below.

Salinity and temperature changes over the past 50 years exhibit strong variability in both the subtropical and subpolar basins (Fig. 1b,c) at a representative depth of 1,000 m. The strong interannual variability of the subtropical property changes stands in sharp contrast to the nearly decadal variability of the subpolar gyre, variability that is more easily mapped onto the broad temporal change of the North Atlantic Oscillation (NAO) index from the 1950s and

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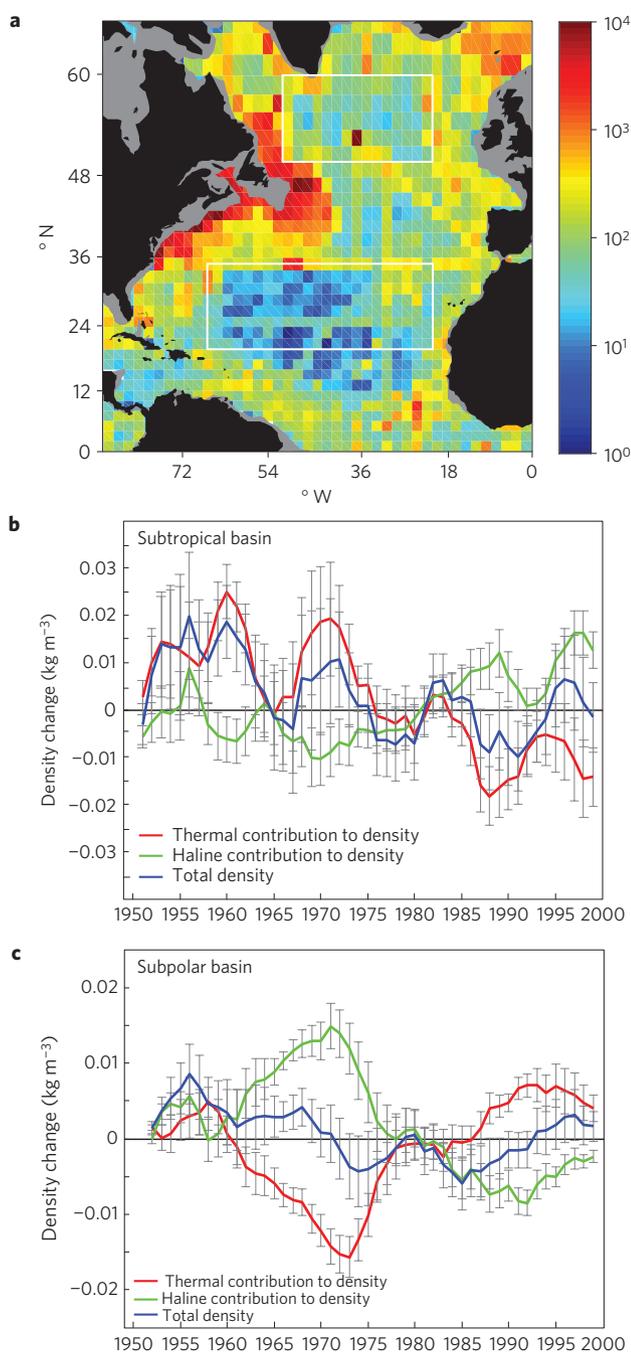


Figure 1 | Historical hydrographic data analysis. **a**, Number of stations per $2^\circ \times 2^\circ$ bin, totalling 508,157: 44,343 from 1950 to 1959; 86,556 from 1960 to 1969; 138,237 from 1970 to 1979; 146,753 from 1980 to 1989; 92,268 from 1990 to 1999. Outlined are the subtropical (11,174 stations) and subpolar domains (37,346 stations) used to construct Fig. 1b,c. Bathymetry <200 m is shaded grey. **b**, Thermal and haline contributions to density³² and their sum averaged over the area outlined in Fig. 1a, at a depth of 1,000 m. Error bars depict standard errors of the quality-controlled data³³. **c**, The same as **b**, except for the central subpolar basin.

1960s—when it was relatively low—compared to the 1980s and 1990s—when it was relatively high^{19,20}. Also revealed from these property changes is the tendency for density compensation in both basins, but particularly so for the subpolar basin where the haline contribution to density is of comparable magnitude to the thermal component. In general, when the waters freshened they cooled, and, likewise, when they became saltier they warmed.

Decomposition of these property changes into the component due to water-mass change and that due to heaving of the isopycnals reveals that the subpolar property changes are largely the result of water-mass changes, whereas the subtropical changes can be largely attributed to wind-induced heaving of isopycnals over time. In spite of the compensation between salinity and temperature, both basins exhibit significant changes in density at a depth of 1,000 m: a decreasing trend is noted for both the subtropical ($-3.3 \times 10^{-4} \pm 6.5 \times 10^{-5} \text{ kg m}^{-3} \text{ yr}^{-1}$) and subpolar regions ($-1.3 \times 10^{-4} \pm 3.0 \times 10^{-5} \text{ kg m}^{-3} \text{ yr}^{-1}$), although the linear change accounts for only 36 and 29% of the variance in the density change for the subtropical and subpolar basins, respectively. Clearly, these statistics, coupled with an inspection of the time series in Fig. 1 and those for other surfaces (Supplementary Fig. S1), cast doubt on our ability to meaningfully interpret the 50-year change as part of a longer-term trend. Nonetheless, the property changes over this 50-year period are significant and of interest to place the dynamical impacts of predicted trends in freshening or warming in the context of strong interannual and decadal variability.

Given the constraints of data availability and distribution, an examination of basin-wide spatial patterns of temperature, salinity and density is accomplished by averaging the historical hydrographic data for two separate periods (1980–2000 and 1950–1970; see Supplementary Fig. S2 for data coverage) with known differences in wind and buoyancy forcing, as represented by the NAO index¹⁹. Though this choice will obscure the impact of the higher-frequency property changes in the subtropical basin, the goal is to yield insight into the property fields of the North Atlantic under two different, known and prominent forcing states. From the property changes shown in Fig. 2 for two composite layers, a picture of compensated, spatially varying anomalies emerges: the subpolar gyre is generally cooler and fresher in the latter time period, whereas the subtropical gyre and the tropics are generally warmer and more saline. In particular, there is a striking division in the property changes at the subtropical gyre–subpolar gyre boundary, as noted earlier in a study of heat-content changes in this basin¹⁶, and more clearly pronounced when the property changes are zonally averaged (Supplementary Fig. S3). This sharp gyre demarcation suggests a strong role for basin-scale dynamics in setting these patterns.

Given the temperature and salinity changes specific to each gyre, an overall density decrease means that the freshening has outpaced the cooling in the subpolar gyre, whereas the warming has outpaced the salinification in the subtropical gyre. It is important to note that the density change is reduced from what we would estimate on the basis of an analysis of temperature alone or salinity alone, and that the similar density tendency in both basins leads to maps of density change (Fig. 2) lacking in gyre specificity. Overall, the analysis of these property changes reveals strong spatial and temporal variability over the 50-year period from 1950 to 2000: most striking is the spatial divide between the subtropical and subpolar gyres, and the temporal divide between the periods of sustained weak and strong NAO forcing.

Impact of density changes on sea level

What are the consequences of these density changes? A direct impact of density change is sea-level change. A map of the rate of sea-level rise evaluated from the former to the latter 20 year time period reveals a general rise in sea level, reaching $3\text{--}4 \text{ mm yr}^{-1}$ in the mid-latitudes (Fig. 3). This rise in sea level is broadly comparable to reconstructions of sea-level rise between 1950 and 2000 on the basis of tide-gauge data, where sea-level rise reaches a peak of typically 3 mm yr^{-1} along 40° N ²¹. However, this regional pattern should not simply be viewed in terms of a persistent trend, because sea level seems to fall along 40° N between 1993 and 2003 at a rate reaching -10 mm yr^{-1} (ref. 22). Hence, the regional pattern

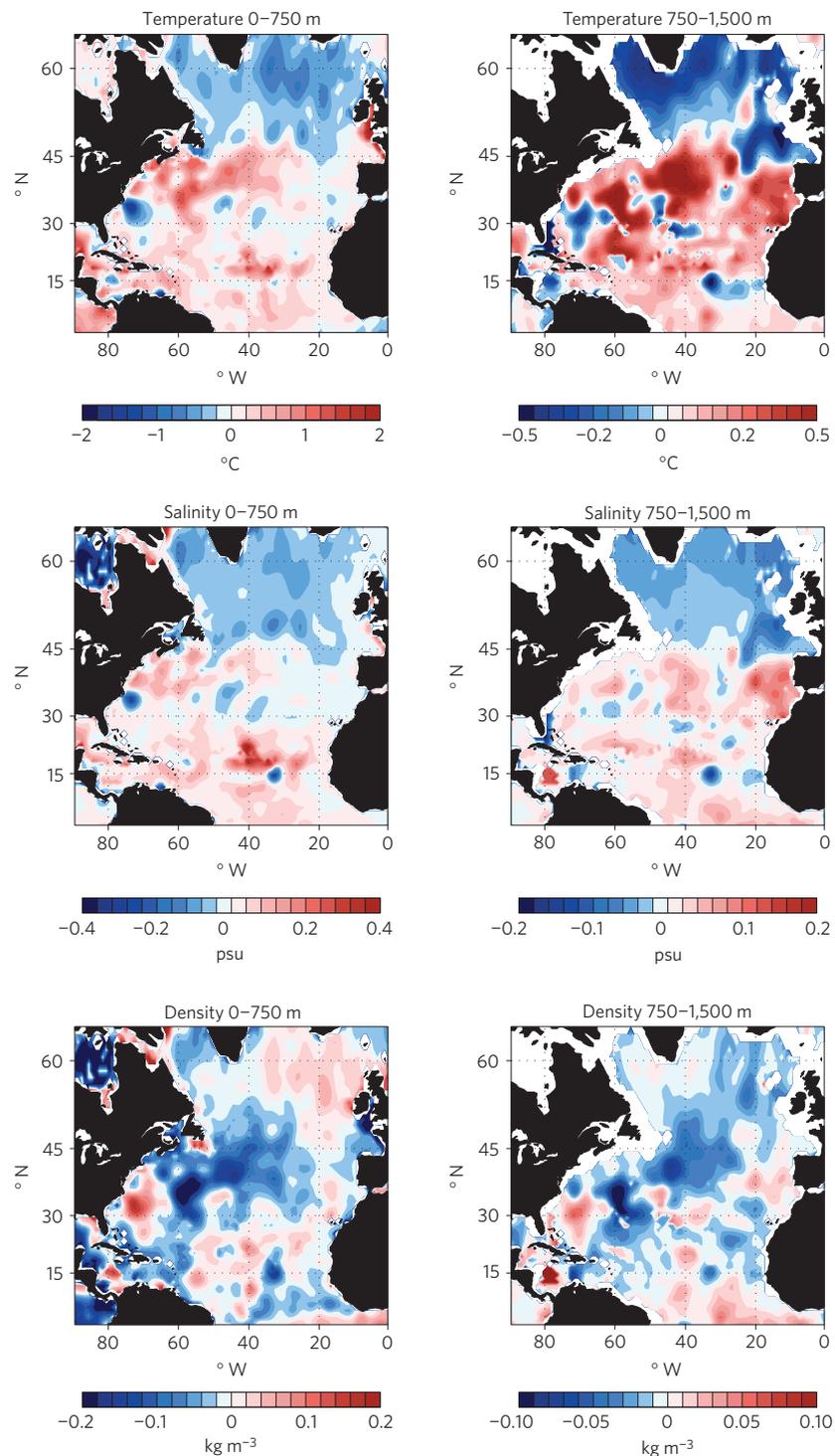


Figure 2 | Spatial fields of temperature, salinity and density changes. Data are binned using a $2^\circ \times 2^\circ$ horizontal grid for the composite layers of 0–750 m and 750–1,500 m: the 1980–2000 time period minus the 1950–1970 time period. Red indicates warming, salinification and densification, whereas blue indicates cooling, freshening and de-densification; note the larger ranges used for the upper waters. Data are plotted after a nine-point smoothing is applied.

of sea-level change seems to be affected by natural variability, in a manner similar to ocean heat content¹⁶, as well as by longer-term climate change.

These diagnosed sea-surface-height changes reflect different and, sometimes, opposing contributions from temperature and salinity changes: the thermal contribution provides a reduction over the subpolar gyre and a rise over the subtropical gyre, particularly its northern flank (Fig. 3b), whereas the salinity contribution

provides a more uniform rise in sea level over the subpolar gyre and much of the subtropical gyre, with localized reduction over the tropics (Fig. 3c). The mean rate of sea-level rise of $0.25 \pm 3.12 \text{ mm yr}^{-1}$, with comparable temperature and salinity contributions of 0.26 ± 3.56 and $0.25 \pm 3.32 \text{ mm yr}^{-1}$, respectively, reveals the dominance of regional variability over basin-averaged changes; see Supplementary Fig. S4 for an estimate of sea-level change that includes changes in the mass field as well as steric effects.

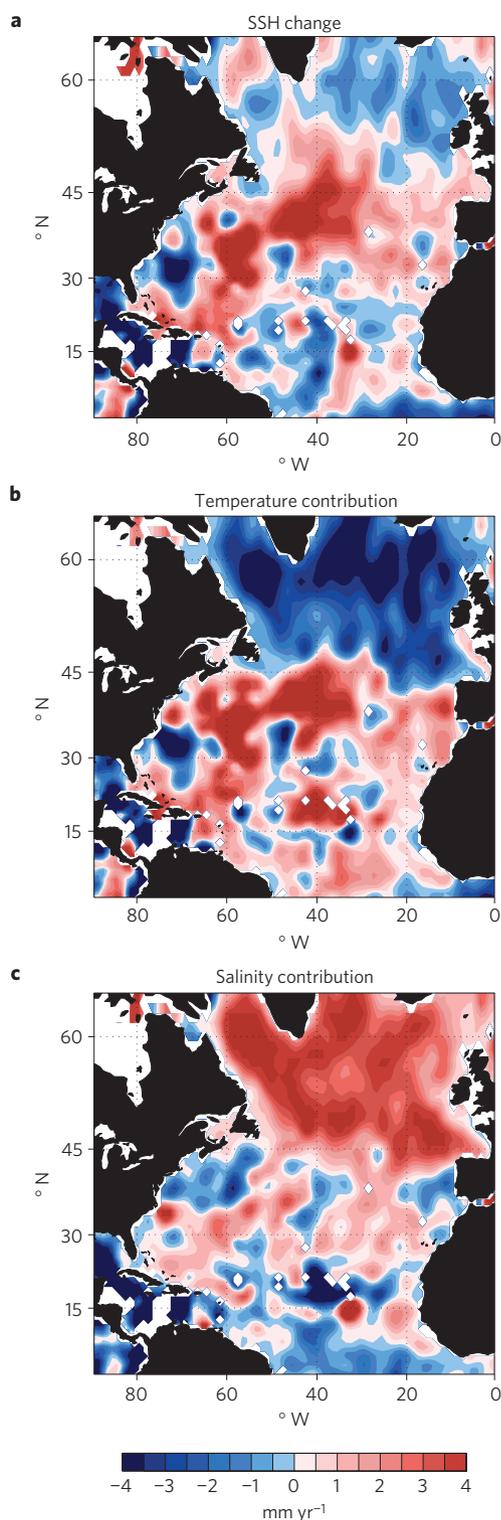


Figure 3 | Sea-surface height changes. **a**, Rate of sea-surface-height change (mm yr^{-1}) between the 1980–2000 and 1950–1970 periods (red is an increase in time, blue is a decrease) on the basis of the density fields for each period. **b**, Temperature contribution to the estimate in **a**. **c**, Salinity contribution to the estimate in **a**. The basin-mean rates of sea-level rise from the temperature and salinity contributions are 0.26 ± 3.56 and $0.25 \pm 3.32 \text{ mm yr}^{-1}$, respectively.

Impact of density changes on the MOC

The dynamical consequence of property changes for the MOC depends on the zonal contrast in density: the difference in density

between the western and eastern boundaries of the basin is directly linked to the strength of the MOC (refs 23,24). Indeed, the measurement of density along these boundaries has formed a central part of the ongoing daily monitoring of the overturning along 26° N since 2004 (refs 9,25). Not surprisingly, for our analysis of density changes between the two 20-year periods, there are insufficient boundary data to provide a robust estimate of the overturning. Rather than ignore any dynamical implications, we explore the possibility that the interior density field has been sufficiently sampled to constrain a model assessment of the overturning. Our approach is as follows: for each 20 year period, the average temperature and salinity fields at 1° horizontal resolution are used to initialize the MIT circulation model over the North Atlantic²⁶; temperature and salinity from a global inverse model²⁷ are used to initialize the rest of the domain. After initialization, the circulation model is integrated for 18 months to enable the density field to dynamically adjust through boundary waves propagating around the basin²⁸. The MOC streamfunction is then calculated from these adjusted fields. This method was tested using output from a global inverse model by comparing the MOC reconstructed from the model's density field with the model 'truth', namely the MOC calculated with the model's velocity field. The favourable comparison (Supplementary Fig. S5a) lends credence to our method and suggests that hydrographic observations should be an important constraint on state-estimate models.

Using the historical hydrographic data, the average MOC for the two time periods reveals the expected structure: northward transport of light water replaced at depth with a southward transport of dense water (Fig. 4a). The overturning transport reaches a maximum of $\sim 16 \text{ Sv}$ at around 45° N , with the transport changing sign near a depth of 1,300 m. The difference between the estimates for these two time periods (Fig. 4b) reveals a gyre-specific pattern: the overturning during the latter time period is slightly weaker over the subtropical gyre by -1.5 Sv , but slightly stronger over the subpolar gyre by typically 0.5 Sv . The weaker overturning for the subtropical gyre is concomitant with a weakening of the east–west density gradient in the thermocline waters (Fig. 5a). This weakening results from the westward warming over the upper 1,500 m (Fig. 2), producing a thickening of the thermocline, a rise in sea level and a reduction in the northward velocity shear, the latter consistent with the model prediction of a slight weakening in the overturning. Over the subpolar gyre, there is a more complicated picture (Fig. 5a): the westward freshening over the upper 500 m actually suggests a weakening in the east–west density gradient and a decrease in the northward velocity shear, whereas the eastward freshening at depth suggests a strengthening in the east–west density gradient and an increase in the northward velocity shear; see Fig. 2c and Supplementary Fig. S6c. The latter process dominates in the model adjustment, leading to a slight strengthening in the overturning. The impact of these changes in the lower thermocline argues for full-depth measures of the density field to accurately assess overturning changes.

The robustness of the estimate for the overturning, and indeed the noted changes in the overturning circulation, depends crucially on the representativeness of the hydrographic data used to initialize the model integration. To assess the effect of data uncertainties on the overturning estimate, multiple integrations of the model are run, all identical save for the initial fields, which are selected randomly on the basis of the standard errors for the density field for each time period. The collection of these ensemble runs (Fig. 4c) qualitatively shows the envelope of possible overturning changes given the errors in the density field, but also yields a quantitative measure of the robustness of the overturning estimate (Fig. 4d): the overturning has weakened over the subtropical gyre by $-1.5 \pm 1 \text{ Sv}$, but strengthened over the subpolar gyre by $0.8 \pm 0.5 \text{ Sv}$.

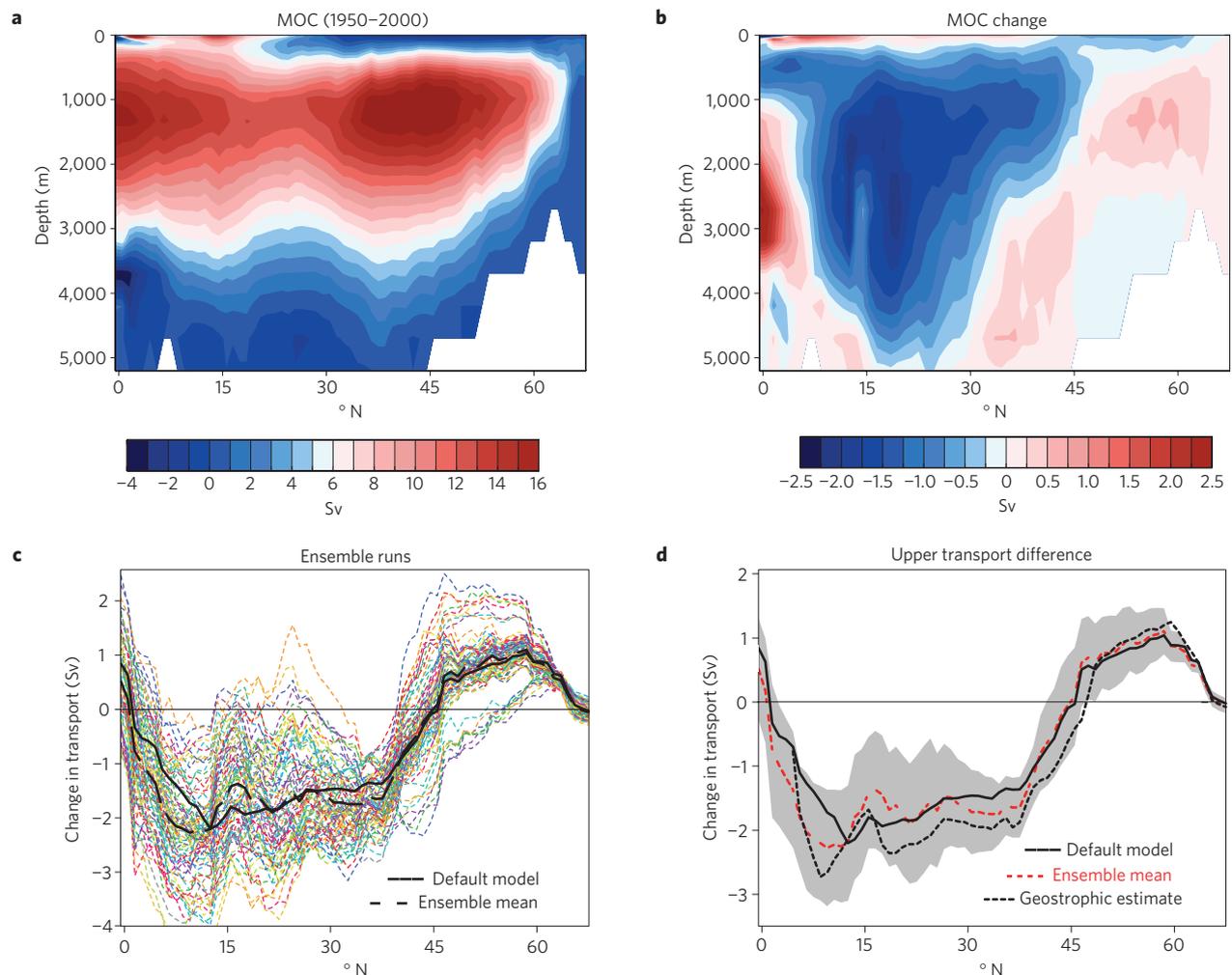


Figure 4 | Changes in the meridional overturning circulation. **a**, Estimate of the mean MOC streamfunction (Sv) evaluated from the MIT model initialized with historical hydrographic data averaged from 1950 to 2000. **b**, Change in MOC (Sv) from 1950–1970 to 1980–2000. **c**, 80 ensemble estimates of the MOC change (Sv), evaluated from 100 m to 1,300 m. **d**, Change in MOC (Sv) calculated with the default model (solid line), calculated from geostrophic velocities derived from adjusted density fields (dotted line) and calculated as the average (dashed line) of the ensembles shown in **c**. Grey shading outlines one standard deviation from the mean of the ensembles.

Also evident in Fig. 4d is that the estimate of the overturning on the basis of the adjusted density field is remarkably similar to that calculated from the model's velocity field, underscoring the overriding importance of the geostrophic velocity field (Fig. 5b) to the overturning circulation. Although the winds are ultimately important in affecting the density distribution over the two 20-year periods, the MOC differences are relatively insensitive to the choice of winds during the short dynamical adjustment used to estimate the overturning (Supplementary Fig. S7).

Overshadowing in importance the magnitude of these estimated MOC changes is their spatial pattern: the canonical picture of MOC changes extending over the entire North Atlantic basin does not seem to hold. Instead, MOC changes are found to be gyre specific, in agreement with independent model experiments^{13–15}, but not yet realized with observations. Indeed, this gyre-scale pattern mimics that found by comparing model runs that differ only in their wind forcing¹³, strongly suggesting that the observed overturning changes estimated here are primarily attributable to the different density distributions arising from contrasting wind forcing between high- and low-NAO periods. Modelling studies lead us to expect basin-wide MOC changes only when buoyancy forcing dominates, presumably on longer timescales than the interannual and decadal timescales afforded by the current observational database.

An intriguing question is the mechanism by which the property and overturning changes could be causally related. Given the paradigm of high-latitude buoyancy forcing producing basin-wide overturning changes, we would expect increases in ocean heat content in the subtropical gyre to result from a strengthening in the overturning. Paradoxically, the reverse holds: heat-content gain in the latter period is associated with a weakening in the subtropical overturning. Such an association is explained causally: anomalous wind forcing associated with the positive NAO state leads to a deepening of the subtropical thermocline through increased Ekman pumping, which in turn leads to a redistribution of heat in the basin and a gain in heat content over the subtropical gyre^{16,28}. Wind-induced redistributions of heat, as well as those of freshwater, that alter the west–east contrast in density across the basin will then impact the MOC. With this causal link, the overturning circulation is not driving the property changes, but is instead responding to them. Clearly, this causality needs to be tested with long-term measurements of property and overturning changes, as well as a dynamical model that can realistically link the two.

Finally, though recent interest in the MOC has focused on the possibility of long-term trends due to changes in buoyancy forcing, identifying this signal is problematic and challenging. This study emphasizes how property changes and overturning

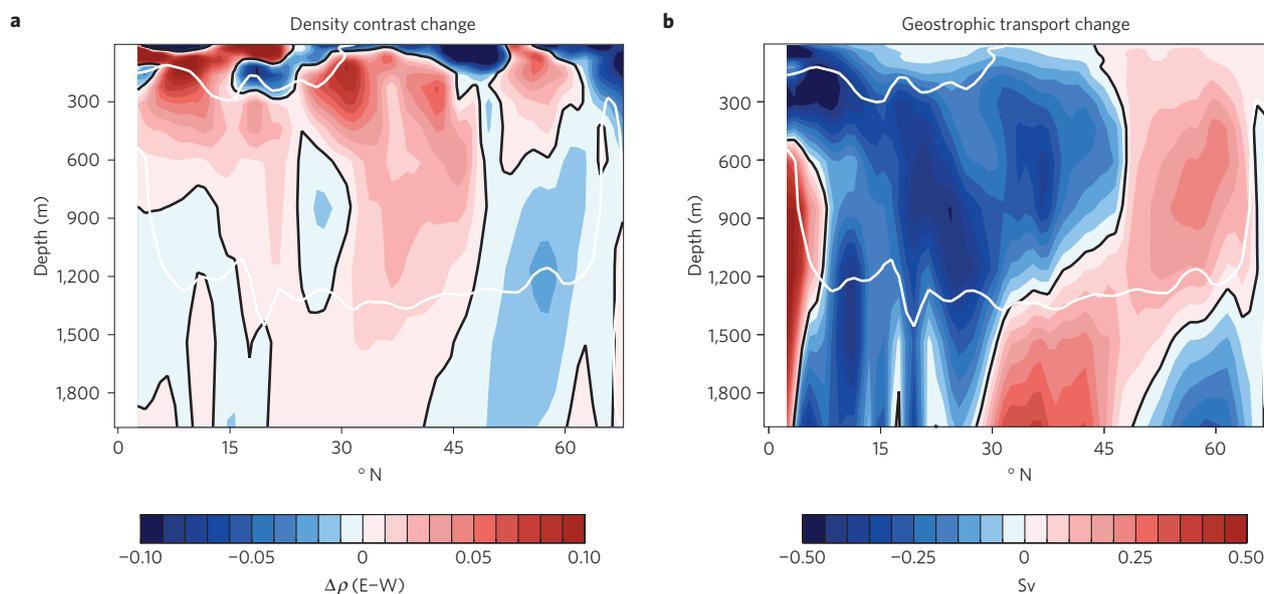


Figure 5 | Relationship of MOC changes to observed density field. **a**, Density difference (kg m^{-3}) between the eastern and western boundaries in the model fields after 18 months of forward integration and dynamical adjustment. A weakening (red) in the density contrast is consistent with reduced vertical shear in northward velocity, whereas a strengthening (blue) indicates increased vertical shear. **b**, Change in geostrophic transport (Sv) for each depth bin from the latter to the former time period after 18 months of model integration. Thick white lines on both panels are zero contours of the meridional transport, positive above typically 1,300 m.

changes are gyre specific. Thus, the MOC variability⁹ measured at 26° N might only be representative of changes in the subtropical gyre, as suggested by the MOC reconstructed at 41° N from ARGO data²⁹ and inferred along the North American east coast from sea-level variability³⁰. Furthermore, the recent reversal of property trends in the subpolar basin^{6,31} suggests that a corresponding reversal of the overturning pattern reported here is perhaps underway. Given the increasing availability of density data, it should soon be possible to estimate the spatial and temporal variability of the MOC in more detail, a necessary goal before a reliable assessment of anthropogenic-induced trends can be made.

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Author contributions

M.S.L. led the data study and its interpretation and R.G.W. led the modelling study and interpretation. V.R. conducted the modelling study and developed the model-data analysis. M.S.C.R. conducted the historical-data analysis. M.S.L. and R.G.W. jointly wrote the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at <http://npg.nature.com/reprintsandpermissions>. Correspondence and requests for materials should be addressed to M.S.L. or R.G.W.

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In the version of this Letter originally published, “ -0.8 ± 0.5 Sv” in the fifth sentence of the abstract should have read “ $+0.8 \pm 0.5$ Sv”. This error has now been corrected in the HTML and PDF versions of the text.