Intensification of the Atlantic subpolar gyre

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Abstract. In the 1990s, the subpolar gyre warmed, contracted westward and weakened, as evidenced by changes in maps of the subpolar sea surface height (SSH) anomalies [Häkkinen and Rhines, 2004, Hátún et al., 2005, Häkkinen and Rhines, 2009]. This period followed the Labrador Sea deep convection years ending in 1994, and corresponds to a restratifying period across the deep Labrador Sea, with waters below 1000 m becoming warmer, saltier and lighter [Lozier et al., 2010]. Here, we revisit the gyre index from altimetry and show that over 2013–2015, the North Atlantic subpolar gyre has been intensifying and expanding eastward, associated with the return of deep convection in the Labrador and Irminger Seas [Yashayaev and Loder, 2016, de Jong and de Steur, 2016]. Comparing SSH anomalies to dynamic thickness anomalies (ΔD) from objectively mapped hydrographic data, we find that the SSH anomaly used for the gyre index at 57°N, 52°W corresponds most closely to the dynamic thickness anomalies between 700–2500 m. Using a 50-year record of ΔD, we show that periods of a stronger gyre correspond to periods of deep convection associated with persistent positive North Atlantic Oscillation conditions. Based on this evidence, and the recent return of deep convection, we speculate that the strength of the Atlantic meridional overturning circulation, recently in decline [Smeed et al., 2014], will soon recover.

- **Result:** The subpolar gyre is cooling, expanding and intensifying since 2013. Since the minimum in 2010–2013, the gyre has recovered by about 5 cm. In a numerical model [Böning et al., 2006], this would equate to about a 5 Sv increase in the gyre (or about 10% of the mean).

   (i) **Evidence (Fig. 1):** The EOF analysis of SSH shows a reversal in the principal component for the pattern found in HR2004, and time series of SSH in the centre of the Lab Sea (57°N, 52°W) used in both HR2004 and Böning et al. [2006] to diagnose the strength of the gyre.

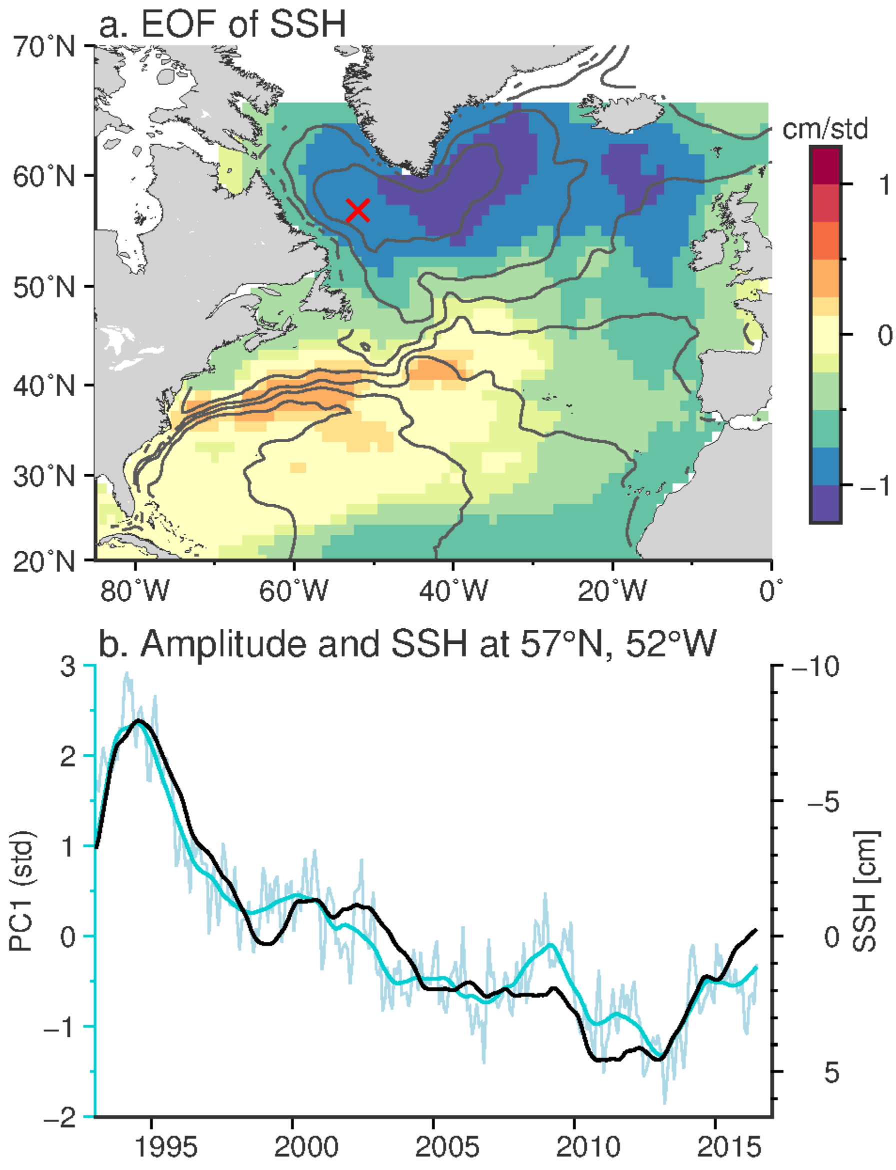

Figure 1. (a) EOF1 of monthly, deseasonalised SSH and (b) it's principal component amplitude (black). Contours show the mean dynamic topography. In (b), the cyan line is the principal component smoothed with a 2-year Tukey filter and the red line shows a smoothed SSH from 57°N, 52°W in the Labrador Sea.

   (ii) **Evidence (Fig. 2):** Extracting a zonal segment of SSH across 57°N shows that SSH at the centre of the Labrador basin (around 52°W) has been rising (consistent with (a)). Using the contours of SSH to indicate the gyre extent, we see that the gyre contracted in the 90s by about 500 km (westward shift of the contour). It shows a slight expansion now of perhaps 200 km.

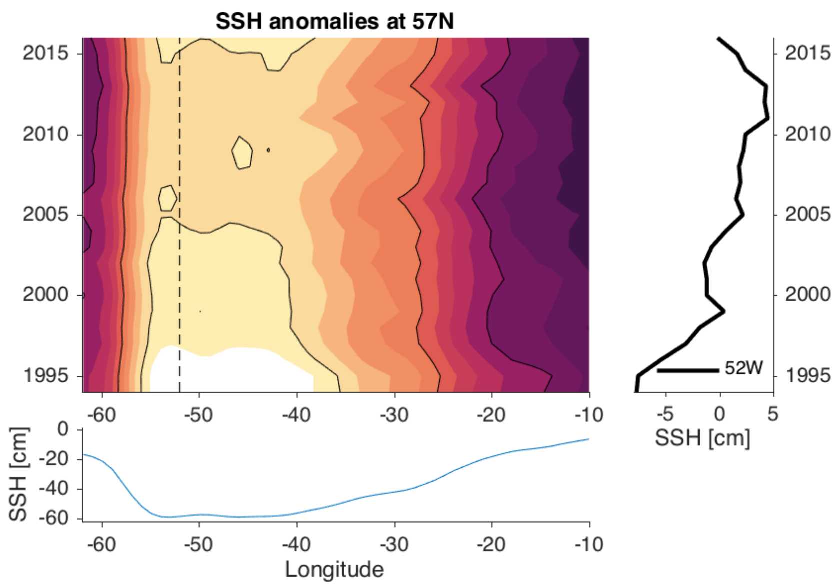

Figure 2. (a) The evolution of SSH along 57°N in the subpolar gyre. The strong gyre in the 1990s can be seen by the deep SSH anomaly around 50°W, followed by a weakening through 2010 (raising of SLA at 52°W, and a subsequent deepening at 52°W. The slight eastward expansion can be seen in the black contours of SSH, where around 28°W, the contour has moved eastward since 2013. (b) Time series of SSH at 52°W. (c) Time average profile of SSH along 57°N. The southern tip of Greenland is around 45°W.

- **Result:** The gyre index can be constructed from dynamic thickness between 700–2500 m. Shows that gyre circulation changes are driven by temperature rather than salinity.
  - (i) **Evidence (Fig. 3):** Dynamic thickness anomaly can be calculated between any two depth ranges. At 57°N and 52°W in the Labrador Sea, we compare the dynamic thickness anomaly between a sliding upper range of 0–3500 m and a sliding lower range of 0–3500 m with the SSH anomaly at the same location. Both can be expressed in units of cm. The RMS error is minimised for an upper limit around 700 m and a lower limit below 2000 m (Fig 3a), while the correlation is maximized for a lower limit around 2500-3000 m (Fig. 3b). The broad range of values for the lower limit is due to the weaker dynamic thickness anomalies at depth. We conclude that geopotential anomaly (dynamic thickness) between 700–2500 m explains both the magnitude and variability of the altimeter SSH-changes.

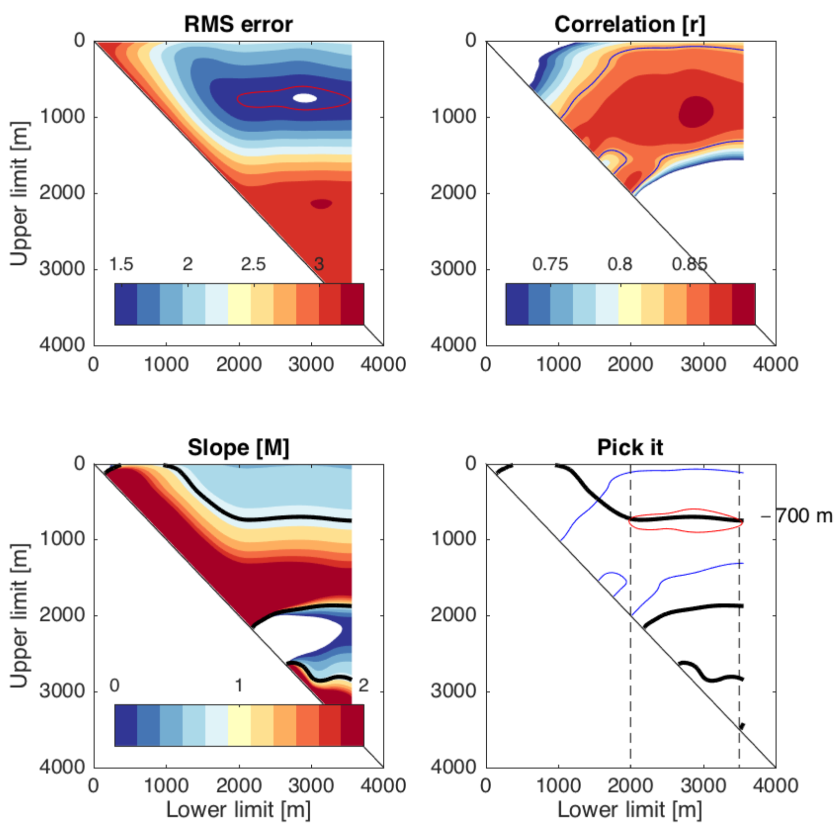

Figure 3. Supplementary? The geopotential thickness anomaly over the range 700–2500 m calculated from the Met Office EN4 dataset [Good et al., 2013]. Time series are scaled by g to have units of centimetres. The time series of SSH (black) is included for comparison. Over the altimetry period, the geopotential anomaly at depth captures the variability and magnitude of the SSH changes, indicating that the changes are present in the hydrographic data.

(ii) **Evidence (Fig. 4):** We compare the time series of dynamic thickness (700–2500 m) with SSH anomalies at the centre of the Labrador basin (Fig. 4). Both the anomalies and variability are well-represented. The Decompositions of geopotential anomaly (or density) into contributions from temperature and salinity show that temperature changes more than explain the observed density changes, with salinity having a compensating effect.

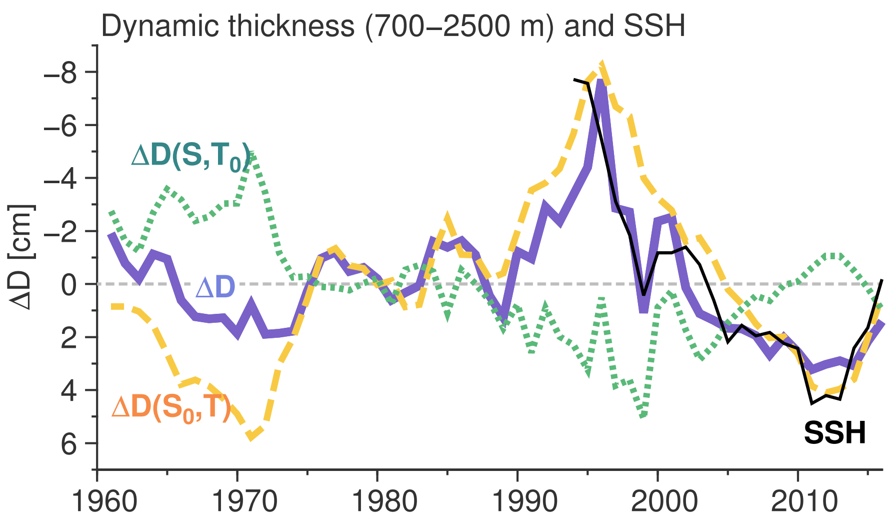

Figure 4. The geopotential thickness anomaly over the range 700–2500 m calculated from the Met Office EN4 dataset [Good et al., 2013]. Time series are scaled by g to have units of centimeters. The time series of SSH (black) is included for comparison. Over the altimetry period, the geopotential anomaly at depth captures the variability and magnitude of the SSH changes, indicating that the changes are present in the hydrographic data.

(iii) **Corroboration, literature:** Both Lozier et al. [2010] and Robson et al. [2016] discuss the TS decomposition of density changes, but do not relate them directly to the gyre index from SSH altimetry.

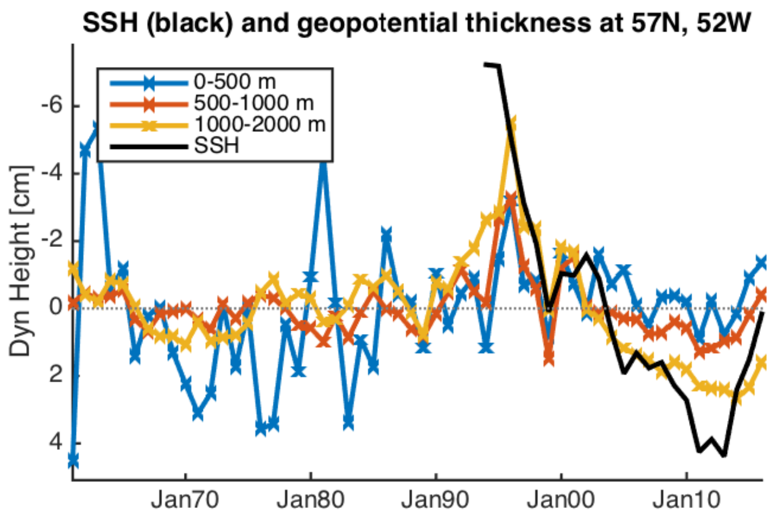

Figure 5. Supplementary? Geopotential thickness anomalies are shown for the 0–500, 500–1000 and 1000–2000 m ranges. Here, it appears that the variability present in SSH over the altimetry period is less discernible in the 0–500 m range than deeper, perhaps due to sparse data sampling aliasing large subannual signals into the annual averages shown here.

- **Result:** The dynamic height index from Fig. 4 and Fig. 5 show negative anomalies in the 1970s, 1980s and early 1990s, as well as since 2013. These time periods correspond to periods of strong convection. They also correspond to periods with persistent positive NAO conditions (Fig. 6).
  - (i) **Evidence (Fig. 6):** SSH and accumulated NAO (where each value represents the sum of that year's index and those from the previous 4 years) covary, with peaks in accumulated NAO and reduction in dynamic thickness associated with periods of convection. The changes in geopotential anomaly are consistent with a spinup of the gyre and overturning (from literature).
  - (ii) **Corroboration from literature:** Gyre spinup is consistent with the ocean response to a persistent positive NAO, when the WSC anomalies support a stronger northward Sverdrup transport (2013/14, 2014/15 and 2015/16) [Eden and Willebrand, 2001]. Positive NAO is also associated with strong heat loss from the subpolar gyre and deep convection.

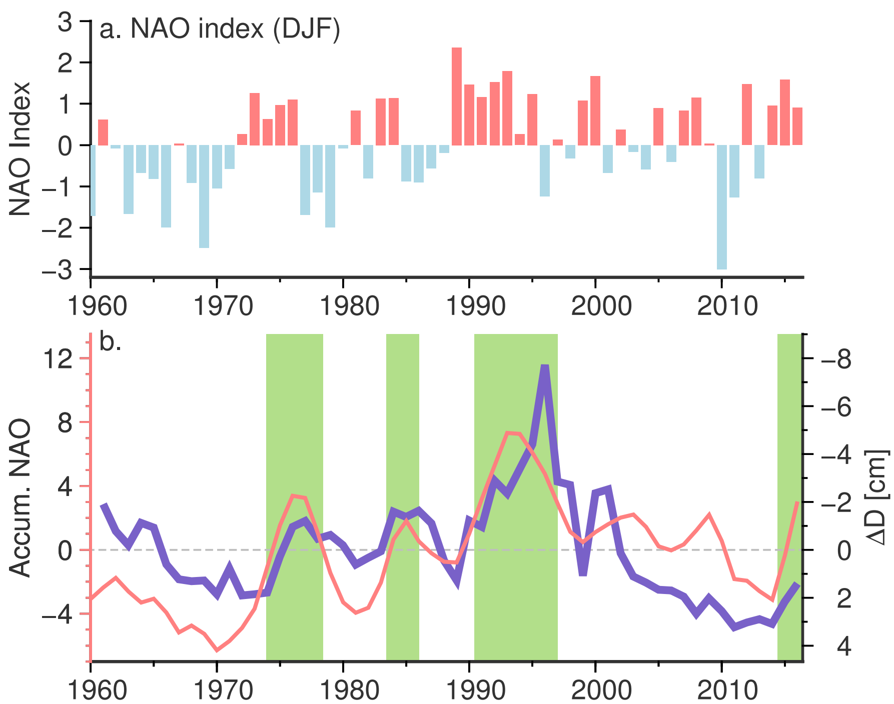

Figure 6. (a) the NAO index (Hurrell-PC based, DJF averages), (b) Accumulated NAO index and dynamic thickness anomaly from 57°N, 52°W in the Labrador Sea. The NAO values are accumulated over 5 years, where each value represents the sum of that year's DJF average along with the previous 4 DJF averages.

(iii) **What next?** The gyre index of HR2004 is supposed to be a measure of the horizontal gyre circulation (confirmed in a numerical model in Böning et al. [2006]). Dynamic height anomalies should be related to SSH anomalies, if they're due to steric changes. Over the past 20 years, we see a strong correspondence between SSH and dynamic height anomalies, but examining the dynamic height anomalies further back in time, we find that the periods when the dynamic height anomalies are negative correspond to periods of known deep convection. So is the present (and past) subsidence of SSH in the Labrador Sea associated with the renewal of deep convection and strengthening of the MOC or is it strengthening of the horizontal subpolar gyre circulation?

- **Summary:** We have shown that the gyre index has reversed and recovered to a typical background state, associated with recent strong atmospheric forcing and deep convection in the Labrador and Irminger Seas.
- **Implications?** Based on these findings, we speculate that the subpolar gyre has been spinning up and associated with it, the overturning in the subpolar gyre [Eden and Willebrand, 2001, Böning et al., 2006], though there may be some lag from the gyre to the the overturning response. The increase in overturning should then be followed by an increase in overturning in the subtropical region (e.g., at 26°N) which may reverse the decade of weakening seen there [Frajka-Williams et al., 2016]. However, the response time of the subtropics is not well known, with models suggesting a lag of 3–9 years Zhang [2010], Bingham et al. [2007], Eden and Willebrand [2001], Pillar et al. [2016]. Identifying a meridionally coherent response is further complicated by the strong, wind-driven interannual variability of the MOC in the subtropics [McCarthy et al., 2012, Mielke et al., 2013, Elipot et al., 2014].
- **Speculation:** At 26°N, the reversal of the subpolar circulation may not be seen until 2021, but the OSNAP results are sure to provide early insights into the ocean response to the subpolar changes of the past couple of years.

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