Mechanisms of decadal and centennial North Atlantic variability in a high resolution global climate model

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

Pablo Ortega, Jon Robson, Rowan Sutton
NCAS Climate/Department of Meteorology, University of Reading, UK

University of Reading

1. Context and Motivation

A necessary step before assessing the performance of decadal predictions is the evaluation of the processes that bring memory to the climate system. These mechanisms are particularly relevant in the North Atlantic, where the Atlantic Meridional Overturning Circulation (AMOC) exhibits large inertia. Recent density observations in the deep Labrador Sea have been used as a proxy of the AMOC strength that points to an ongoing slowdown since the mid 90s (Fig. 1; Robson et al., 2014), a decline also hinted by in-situ observations (RAPID array; Smeed et al., 2014).

This study explores the link of Labrador Sea densities with the ocean circulation and their relationship with the climate in the wider North Atlantic, analysing a 310-year preindustrial control simulation with the HadGEM3-GC2 model (Williams et al., 2015). We address the following questions:

1. What are the processes at the origin of the Labrador Sea density trends?
2. How do Labrador Sea waters affect the AMOC and heat transports?
3. Is there any atmospheric impact anticipated by the Labrador Sea changes?
4. And any feedback mechanism at play?

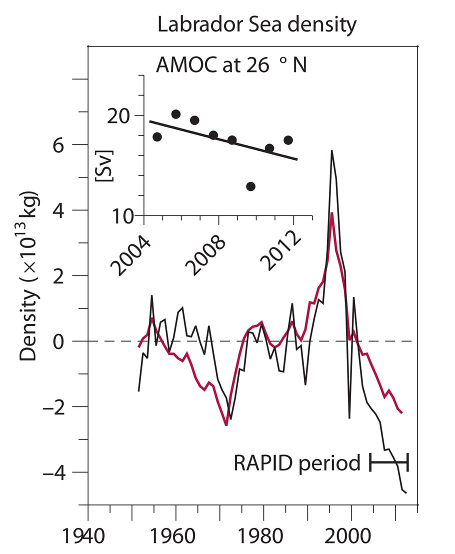


Figure 1: Observations of the potential density of Labrador Sea water at depths of 1,000 to 2,500 m, from two sets of ocean analyses. From Robson et al. (2014).

2. Characteristics of density variability in the Interior Labrador Sea

Vertical coherence of the Labrador Sea density changes

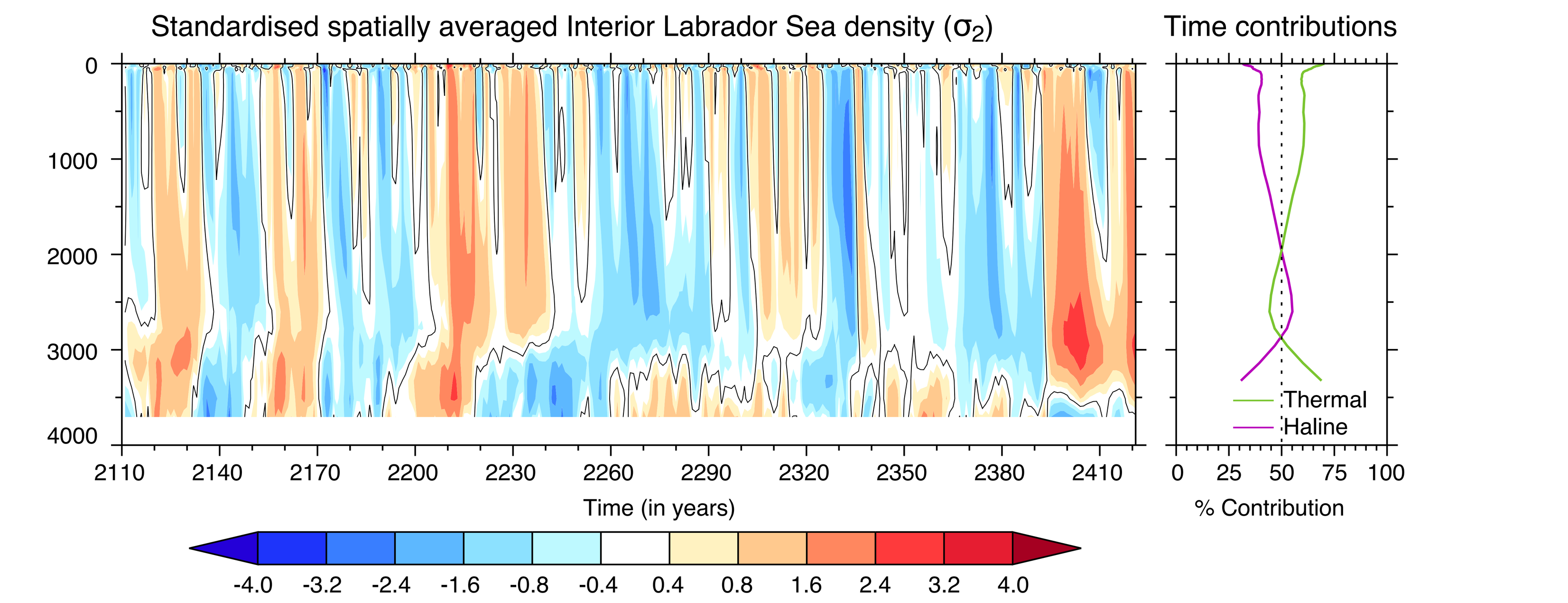


Figure 2: (Left) Hovmoller plot of the standardised anomalies of the spatially averaged Interior Labrador Sea densities. (Right) Time averaged relative contributions of the thermal and haline components to density.

The leading mode of Labrador Sea density variability

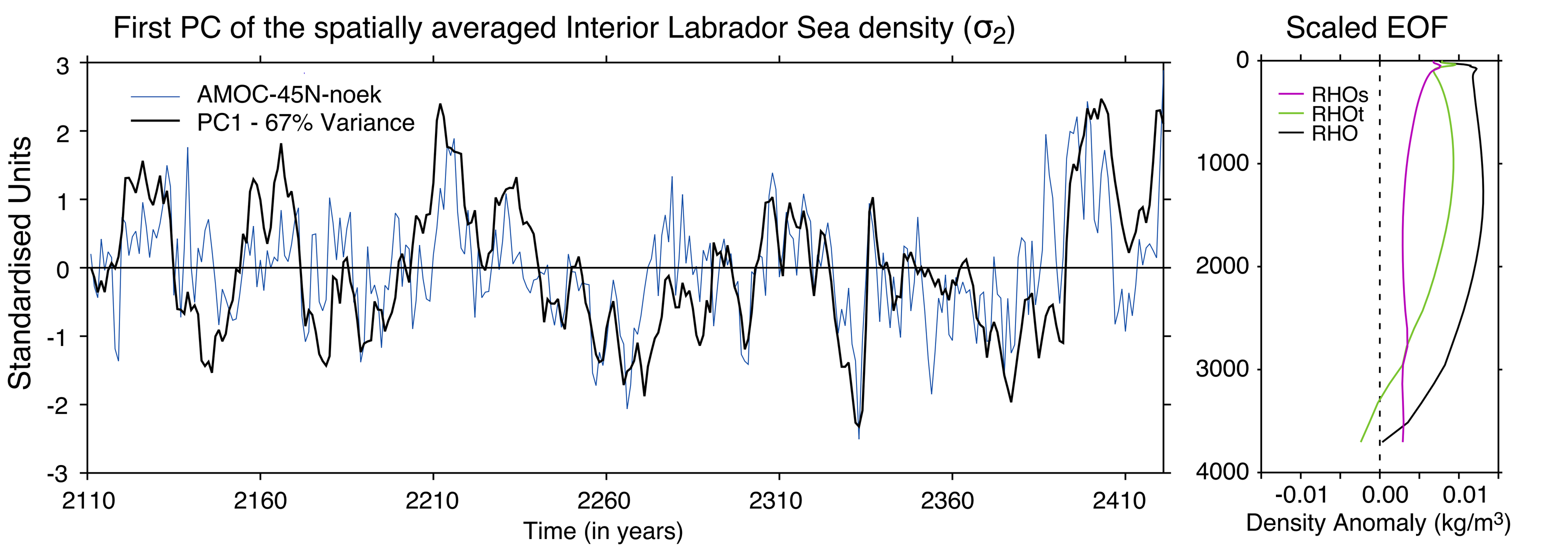


Figure 3: (Left) Evolution of the first PC of the spatially averaged standardised Interior Labrador Sea densities (PC1-ILS) and the AMOC at 45N after removing the Ekman signal (MOI-45N-noek). (Right) Vertical structure of the first EOF (black line), re-scaled to density units multiplying by the standard deviation at each depth level.

► Interior Labrador Sea densities show clear multidecadal changes in GC2, specially evident in the subsurface.
►The leading mode represents a fairly uniform vertical structure, with both temperature and salinity contributing to the density changes. It reproduces most of the low frequency changes in the AMOC at 45N.

4. Drivers of the Labrador Density variability

Atmospheric influence: the role of local surface heat fluxes

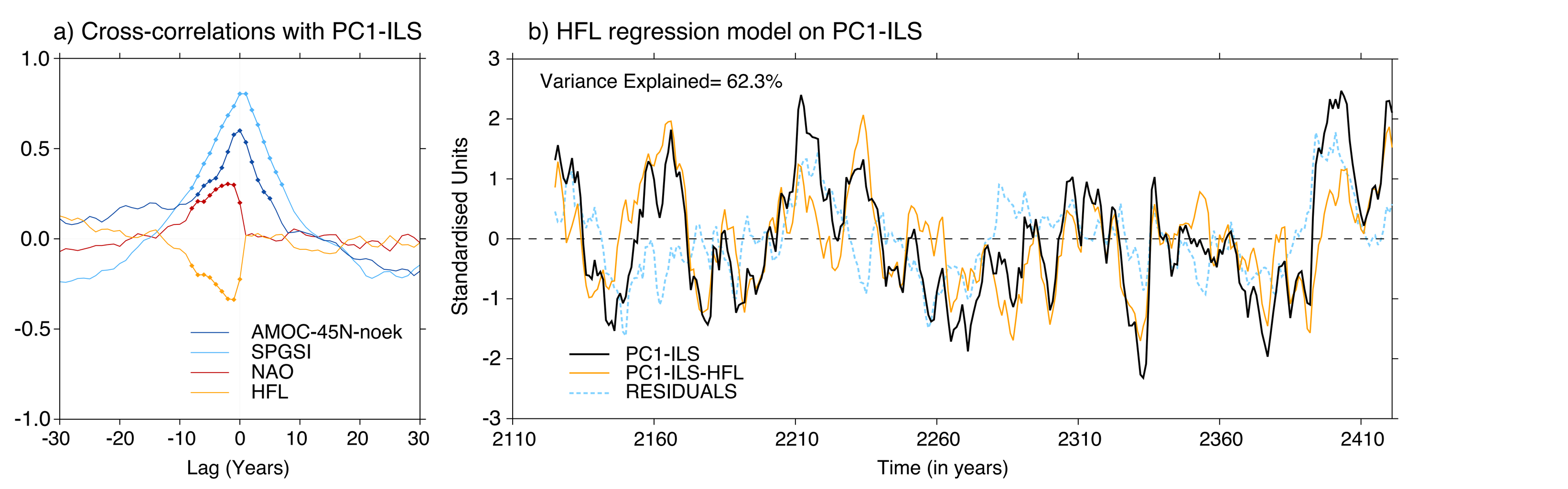


Figure 7: a) Cross-correlations between PC1-ILS and AMOC-45N-noek, SPGSI, the averaged heat fluxes (HFL) in the Labrador Sea Interior and the NAO. Dots denote correlation values exceeding a 95% confidence level. Positive lags correspond to the PC leading the other indices. b) Evolution of PC1-ILS, a regression model based on ILS heat fluxes (PC1-ILS-HFL) and the residuals.

Ocean contributions: two distinct exports through the Denmark Strait

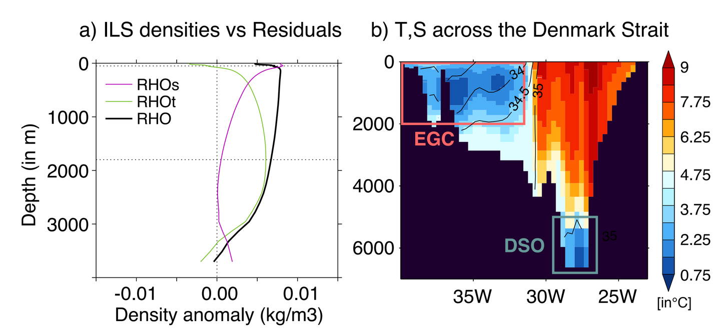


Figure 8: a) Regression of the standardised residuals onto the spatially averaged ILS density components. b) Climatological mean salinity (shaded) and temperature (contours) at 65°N.

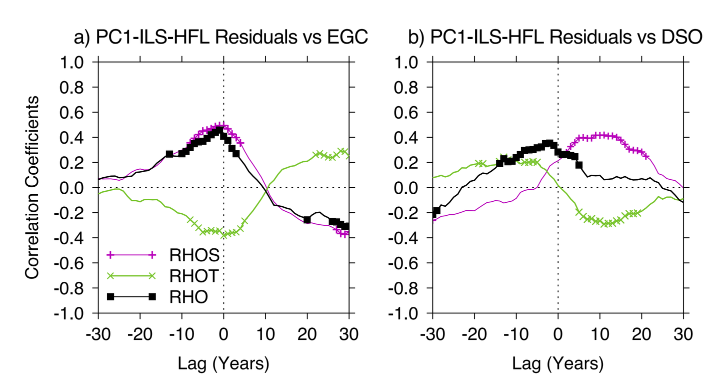


Figure 9: a-b) Cross-correlations between the PC1-ILS-HFL residuals and the density components of EGC and DSO, respectively. Negative lags correspond to the residuals lagging.

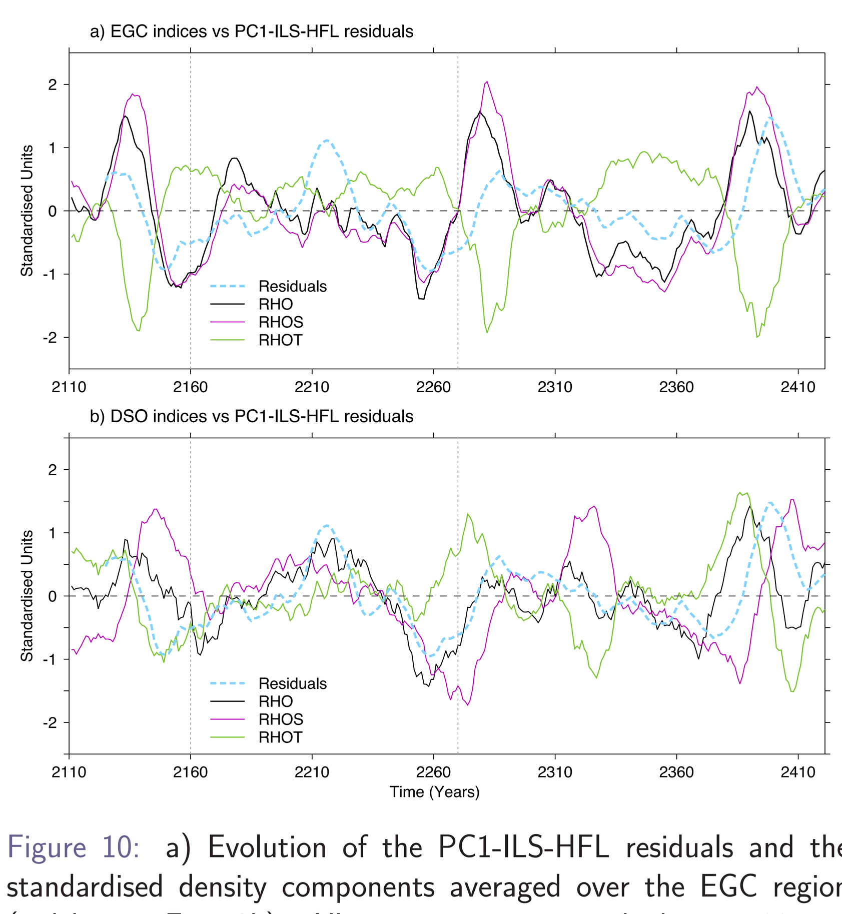


Figure 10: a) Evolution of the PC1-ILS-HFL residuals and the standardised density components averaged over the EGC region (red box in Fig. 8b). All timeseries are smoothed using 11-year running means. b) The same but for the DSO (blue box in Fig 8b).

► More than 60% of PC1-ILS variability is explained by the accumulation of NAO-driven surface heat fluxes.
► Salinity exports by the East Greenland Current explain some large maxima in the PC1-ILS-HFL residuals.
► Centennial ILS density variability relates to thermal and haline signals in the Denmark Strait Overflow.

3.- Labrador Sea Density links with AMOC and OHT variability

Labrador densities and the western boundary current

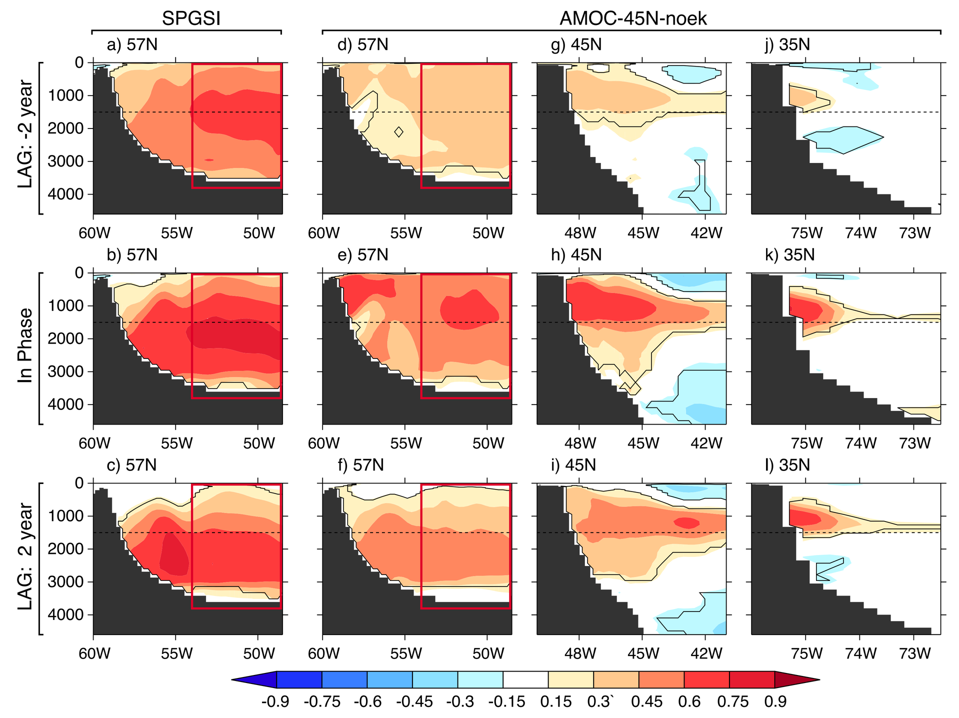


Figure 4: Cross-correlations of the MOI-45N-noek and the Subpolar Gyre Strength Index (SPGSI) with density in three latitudinal sections along the western boundary: 57N (*i.e.* Interior Labrador), 45N and 35N. Correlations significant at the 95% confidence level are highlighted with black contours.

Thermal wind meridional velocity

(From Hirschi and Marotzke, 2007)

$$\tilde{v}(z,x) = \frac{g}{\rho_0 f}\int_{-H}^{z}\frac{1}{L(z)}(\rho_w - \rho_e)dz'$$

where ρ_w, ρ_e represent the density at the west and eastern boundary.

Latitudinal coherence in AMOC/OHT changes

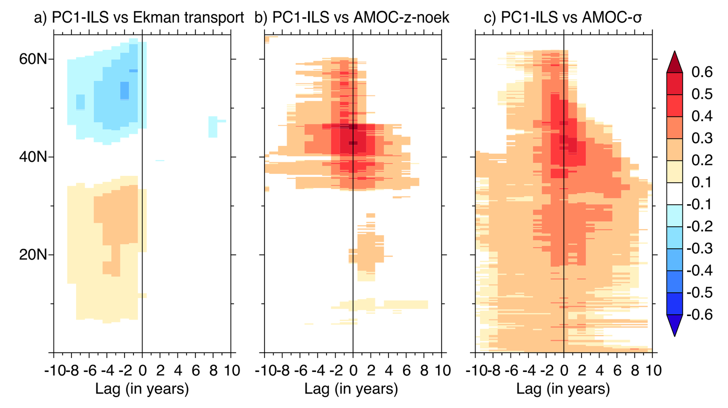


Figure 5: a) Cross-correlations between PC1-ILS and the Ekman transport as a function of latitude. Only values significant at the 95% confidence levels are shown. b-c) The same but for AMOC$_z$-Ekman and the AMOC$_\sigma$. Positive lags indicate that PC1-ILS leads.

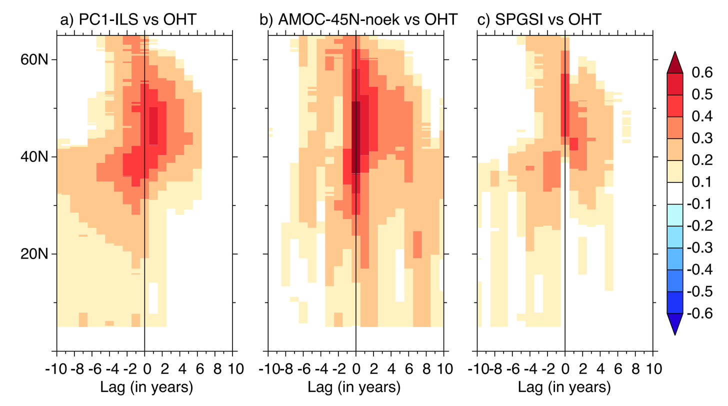


Figure 6: The same as Fig. 5 but between the OHT and the indices PC1-ILS, MOI-45N-noek and SPGSI, respectively. Positive lags indicate that OHT lags.

► Only the upper 1500 m show coherent density changes along the western boundary, as expected for basin-scale AMOC strengthenings. Deeper anomalies are linked to changes in SPG strength.
► PC1-ILS also represents general AMOC and OHT strengthenings particularly evident north of 40N. Two propagation timescales are identified for the AMOC changes.

5. Seasonal atmospheric impacts

Winter NAO response to Interior Labrador density variability

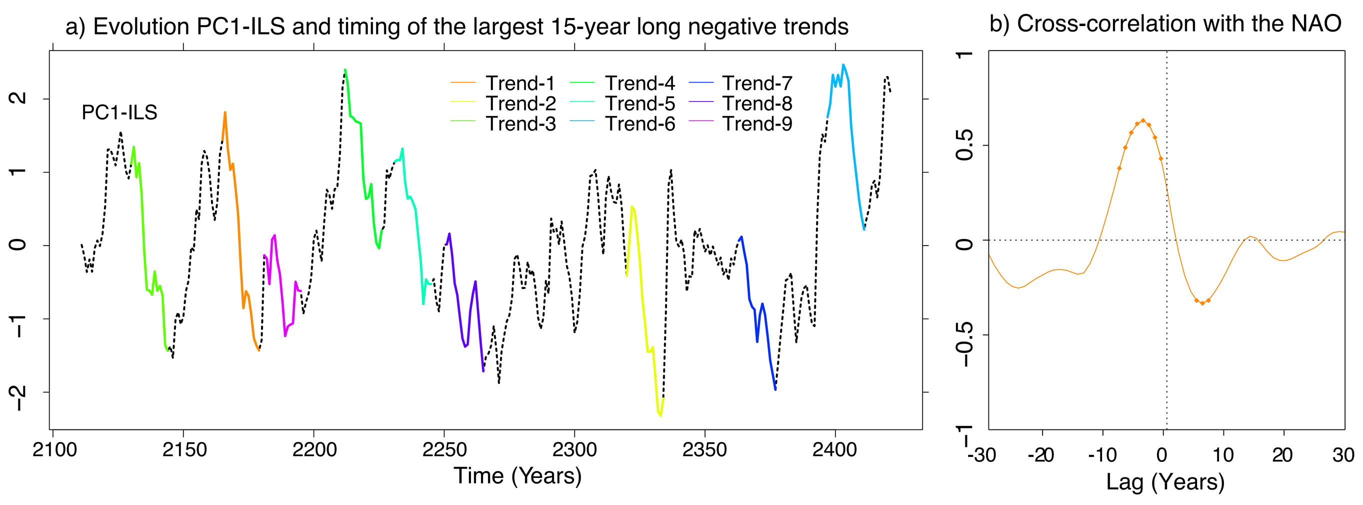


Figure 11: a) The 9 largest non-overlapping 15-year decreasing trends in PC1-ILS. b) Cross-correlation between the 15-year linear-trends in PC1-LAB and the respective trends in the NAO (defined as the pressure difference between Azores and Iceland).

Delayed atmospheric fingerprints of the Interior Labrador density index

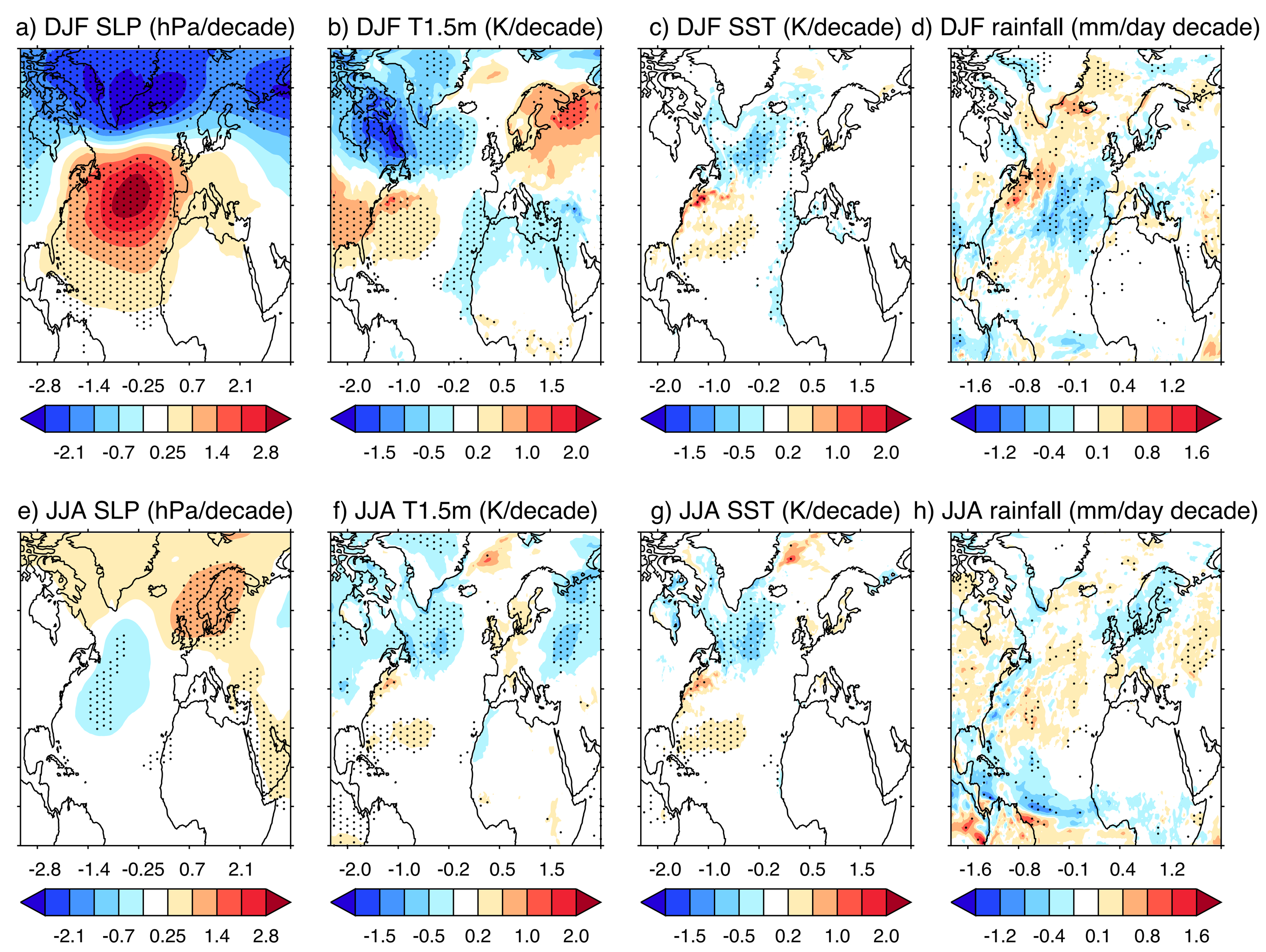
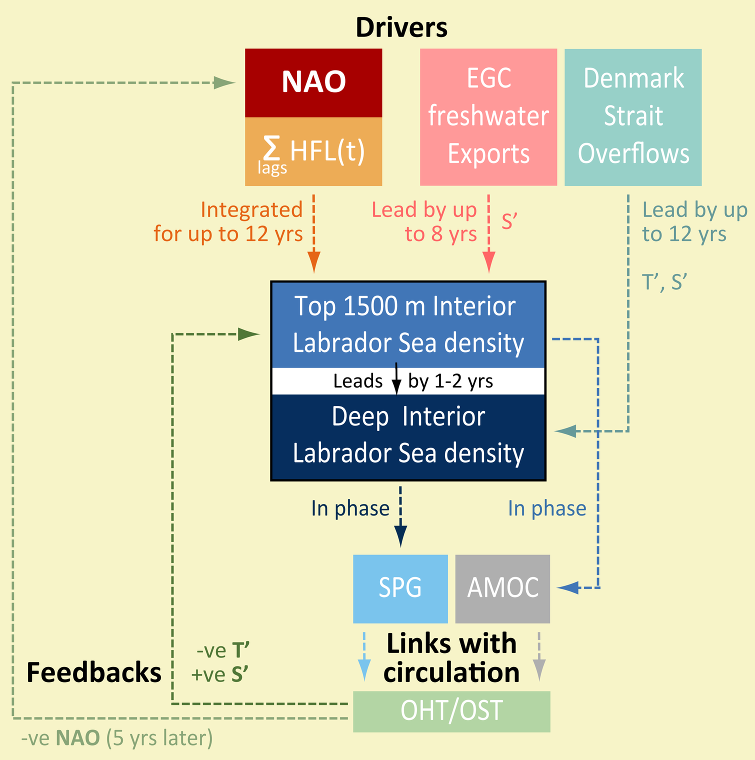


Figure 12: a) Composite of 15-year linear-trends in DJF SLP following the 9 strongest decreasing trends in Fig. 11 [hPa/Decade], where SLP trends are offset by 5 years. Stippling shows where trends are significant at the p≤0.1, based on a Monte-Carlo re-sampling of trends. b-d) The same but now for the DJF anomalies in air temperature at 1.5m [°C/Decade], the SST [°C/Decade] and total rainfall [mm day^{-1} /Decade]. e-i) The same as a-d) but for the JJA anomalies.

► A negative winter NAO seems to be excited in response to the strong decreasing trends in PC1-LAB.
► Important atmospheric impacts appear 5 years the largest PC1-ILS trends, with marked seasonal differences, specially over land. A southward shift in the ITCZ is seen during the summer.

SCHEMATIC OF THE INTERACTIONS



FURTHER WORK

Investigating how the NAO response is established

I. Can we reproduce the previous positive NAO-like pattern in coupled model experiments where the contemporaneous ocean state (to the NAO response) is constrained?

II. And the negative NAO-like trend pattern (not shown) following the Labrador Sea density increases?

III. Which is the particular region forcing this atmospheric response?

IV. Can we identify the processes responsible?

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Hirschi J, Marotzke J (2007) Reconstructing the meridional overturning circulation from boundary densities and the zonal wind stress. J Phys Oce 37: 743–763
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Smeed DA, McCarthy GD, Coauthors (2014) Observed decline of the atlantic meridional overturning circulation 2004-2012. Ocean Science 10: 29–38
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NCAS Climate, Department of Meteorology, University of Reading, Reading, United Kingdom, Mail: p.ortega@reading.ac.uk Website: http://www.met.reading.ac.uk/users/users/2254