Assessing reconstruction techniques of the Atlantic Ocean circulation variability during the past millennium

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1. Motivation

Lund et al. [2006] (L06 hereafter) propose a reconstruction of the Florida Current volume transport (FC; Fig. 1, top) for the past millennium based on zonal density differences in the Florida Strait (red dots, Fig. 1, bottom).

This reconstruction shows a minimum during the Little Ice Age (LIA). A weakened FC/AMOC and associated heat transport could thus have contributed to the cooling of the North Atlantic, Arctic and European regions.

→ We perform model-based pseudo-reconstructions of the AMOC and FC and compare them with their true simulated variability in an attempt to assess the validity of this reconstruction technique. The pseudo-reconstructed FC is, in addition, compared with the actual reconstruction.

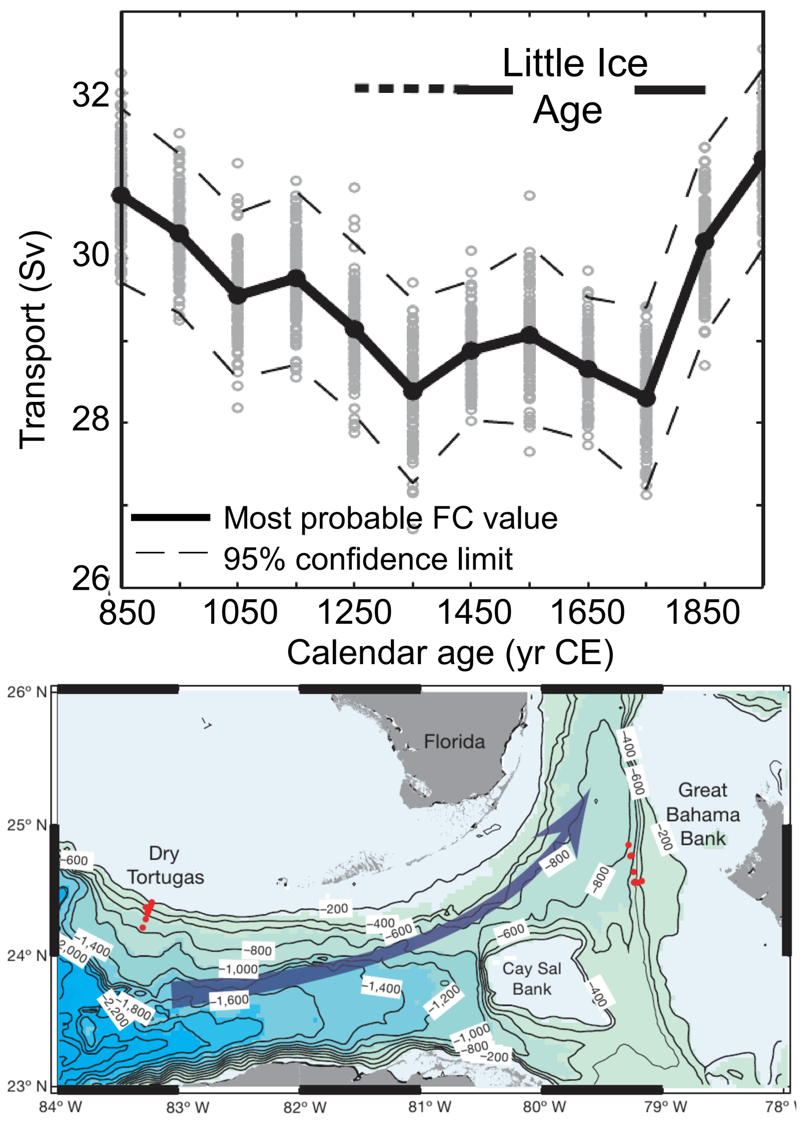


Fig. 1: Transport reconstruction of the Florida Current (*top*). Bathymetric map of the Florida Straits showing core locations (*red circles, bottom*). Modified from L06.

2. Experimental Setup

- ECHO–G: Atmosphere–ocean GCM
  - ECHAM4: T30 (3.75°). 19 vertical levels
  - HOPE–G: 2.8° (0.5° at Equator). 20 levels
- Last millennium simulation: 1000–1990 CE: solar and volcanic as natural forcings, greenhouse gas concentrations as anthropogenic ones (Fig. 2, below; further details in González-Rouco et al. 2006, 2009)

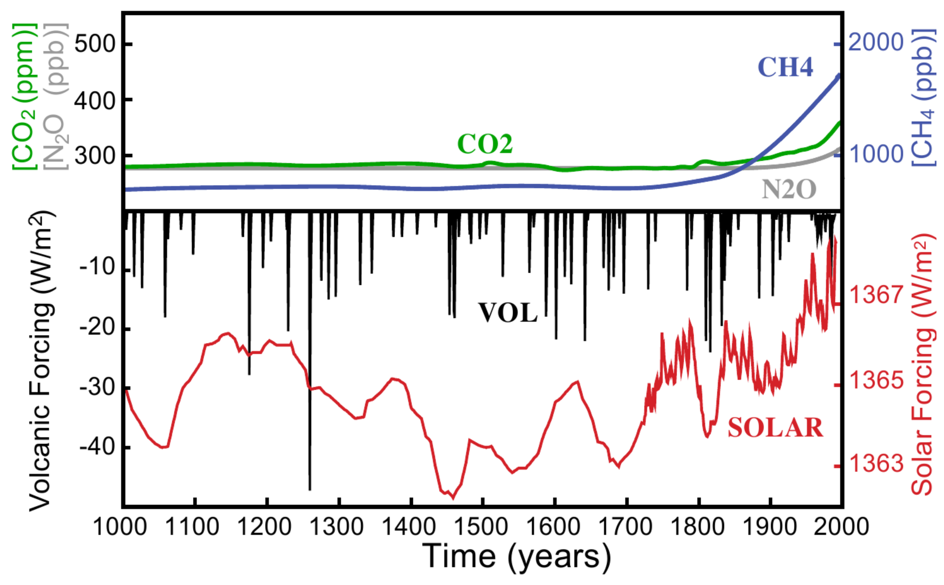


Fig. 2. Imposed natural and anthropogenic forcing factors: solar irradiance (SOLAR), greenhouse gas (GHG) concentrations (CO2, N2O and CH4), and radiative effect of volcanic aerosols (VOL).

3. Methodology

In a nutshell: assuming thermal-wind balance, the meridional FC can be calculated as:

$$FC \propto \int_{-850}^{0} dz' \int_{-850}^{z'} \Delta\rho dz'' \quad (1)$$

$\Delta\rho$ → zonal density difference between two points (triangles in Fig. 3, below)

850 → level of no-motion

We apply in ECHO–G the same methodology followed in L06 to calculate the FC

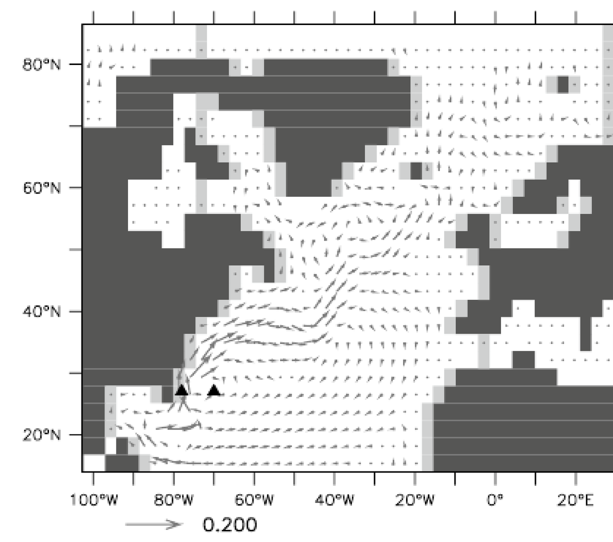
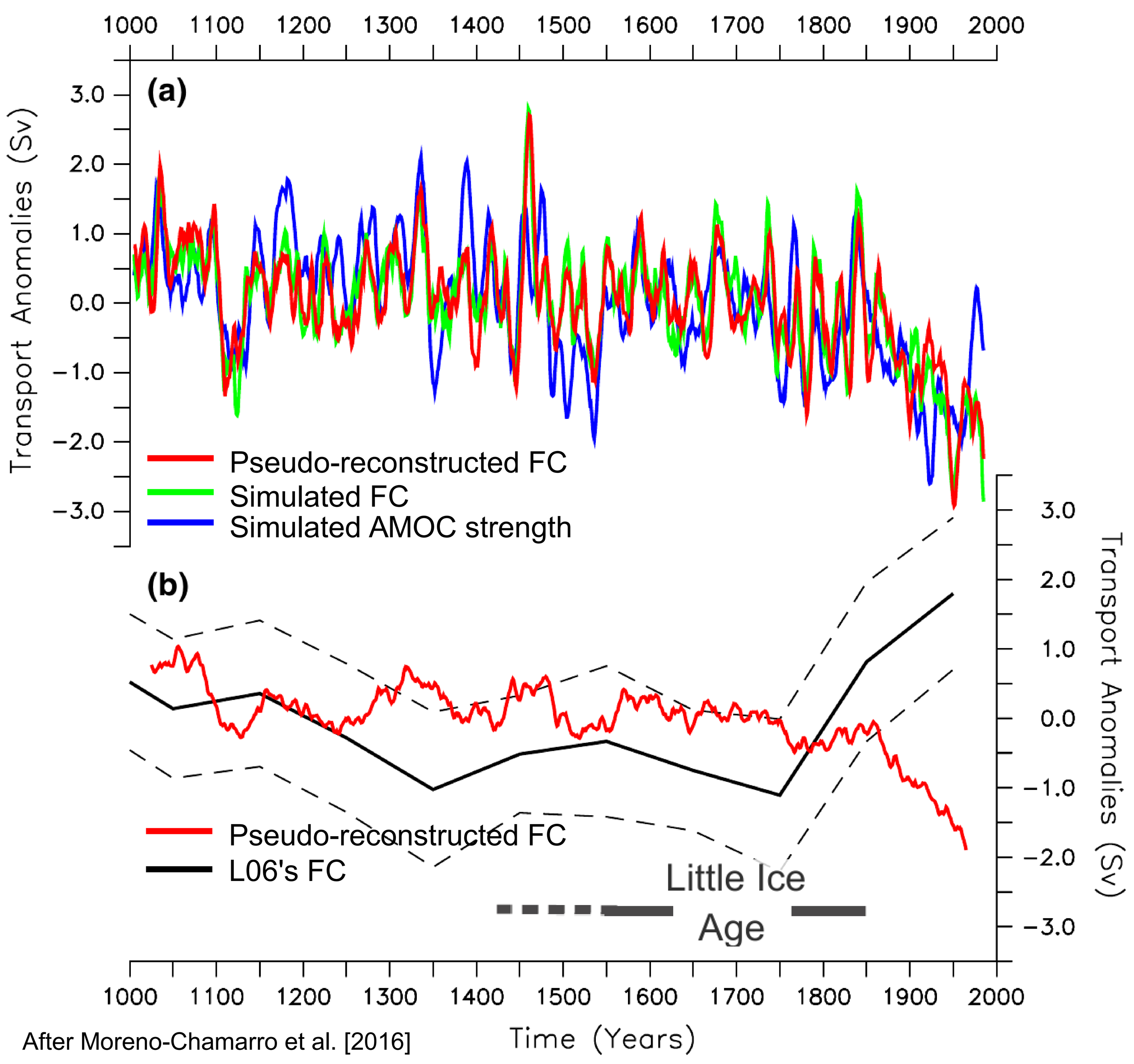


Fig. 3. North Atlantic Ocean surface margins in ECHO–G (*dark gray*). *Triangles*: grid points where densities are selected to calculate the FC in Eq. 1. *Arrows*: simulated oceancurrents in the upper 800 m (in m/s). *Light gray:* coastal grid points.

4. Florida Current Variability



After Moreno-Chamarro et al. [2016]

Fig. 4 (a) In ECHO–G, FC anomalies (with respect to the long-term mean; smoothed with an 11-year running mean) of the pseudo-reconstructed and simulated FCs and AMOC strength (averaged between 35–45°N, at 1500 m depth). **(b)** FC anomalies of the pseudo-reconstruction (as in **a**, but smoothed with a 51-year running mean) and the L06's reconstruction (as in Fig. 1).

Fig. 4a (left) compares the pseudo-reconstructed (red) and actual simulated FCs (green) with the AMOC strength (blue).

- The pseudo-reconstruction captures well the simulated variability above decadal time scales of both the FC and AMOC. This is mostly driven by internal climate dynamics in the preindustrial period (1000–1800 CE) and by increasing GHG afterward (1800–1990 CE).
- Only a relatively small part (~18% of the total variance) of the simulated FC variability is not reproduced by this reconstruction technique. In addition, it tends to overestimate/underestimate the simulated variability above/below 300 m approximately (Fig. 5, right). The largest error is found at the deepest levels (600–850 m).
- The thermal contribution of the zonal density gradient is the one that drives most of the FC variability; salinity opposes but play a minor role (Fig. 6, right).

Fig. 4b (left) compares the pseudo-reconstructed FC (red) and the one estimated in L06 (black).

- No FC/AMOC minimum during the LIA in the model, but at the end of the millennium. This points to:
  - errors in the reconstruction (e.g., $\delta^{18}O$–seawater density relationship, age model),
  - misrepresented processes in the model (because of the relatively coarse resolution; e.g., wind-driven circulation, water cycle, response to external forcing),
  - dominating internal ocean dynamics during the preindustrial period.

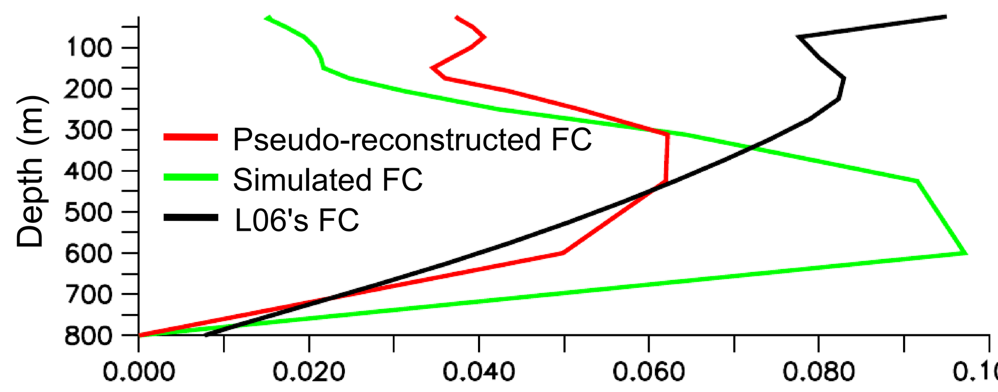


Fig. 5. Standard deviation (in Sv) versus depth of the FCs from Fig. 4 (same colors).

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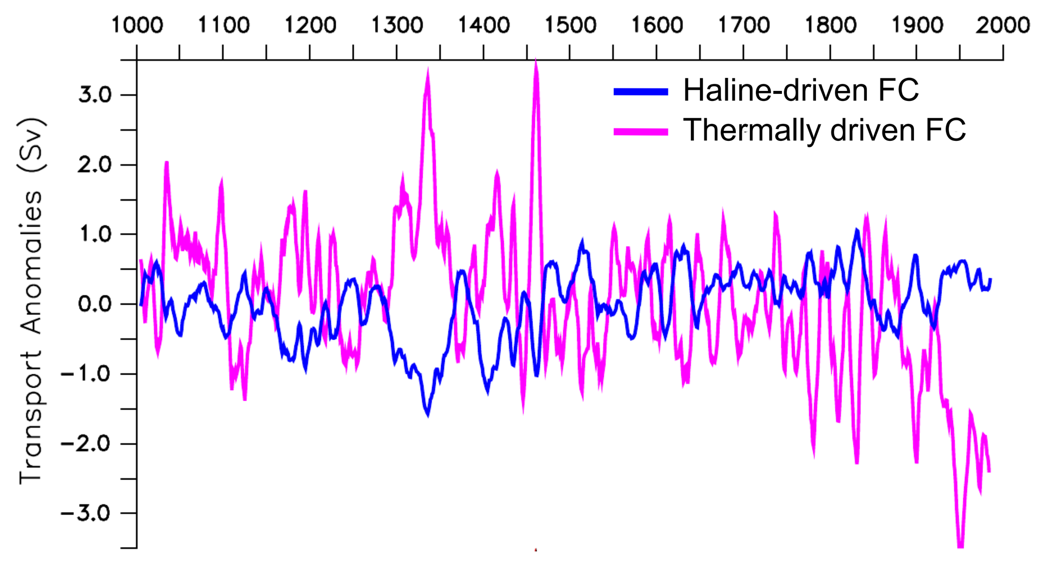

Fig. 6. FC (in Sv) calculated from the haline- and thermally driven contributions to the zonal density gradient, as in Fig. 4a.

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5. AMOC Variability

The AMOC streamfunction can be decomposed into three dynamical components: the external mode, the geostropic shear (or thermal wind), and the wind-driven Ekman transport

$$\psi(z) = \psi_{ex}(z) + \psi_{sh}(z) + \psi_{ek}(z) \qquad (2)$$

where $\psi_{sh}(z)$ can be calculated from the zonal difference in coastal densities along the North Atlantic (light gray shading in Fig. 3; Hirschi and Marotzke, 2007). This methodology is the base of the current in-situ AMOC monitoring [e.g., Kanzow et al. 2007).

In the last millennium simulation, the thermal-wind component reproduces well the spatial pattern of the simulated AMOC (Fig. 7, right) and very well its temporal variability above decadal time scales (Fig. 8, below). The other two terms play a minor role (not shown).

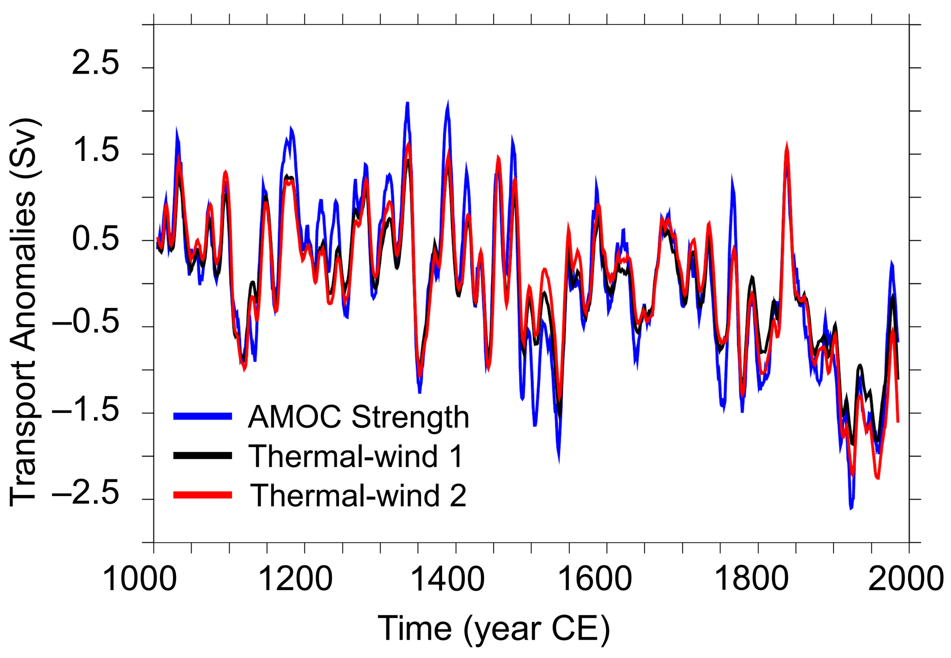
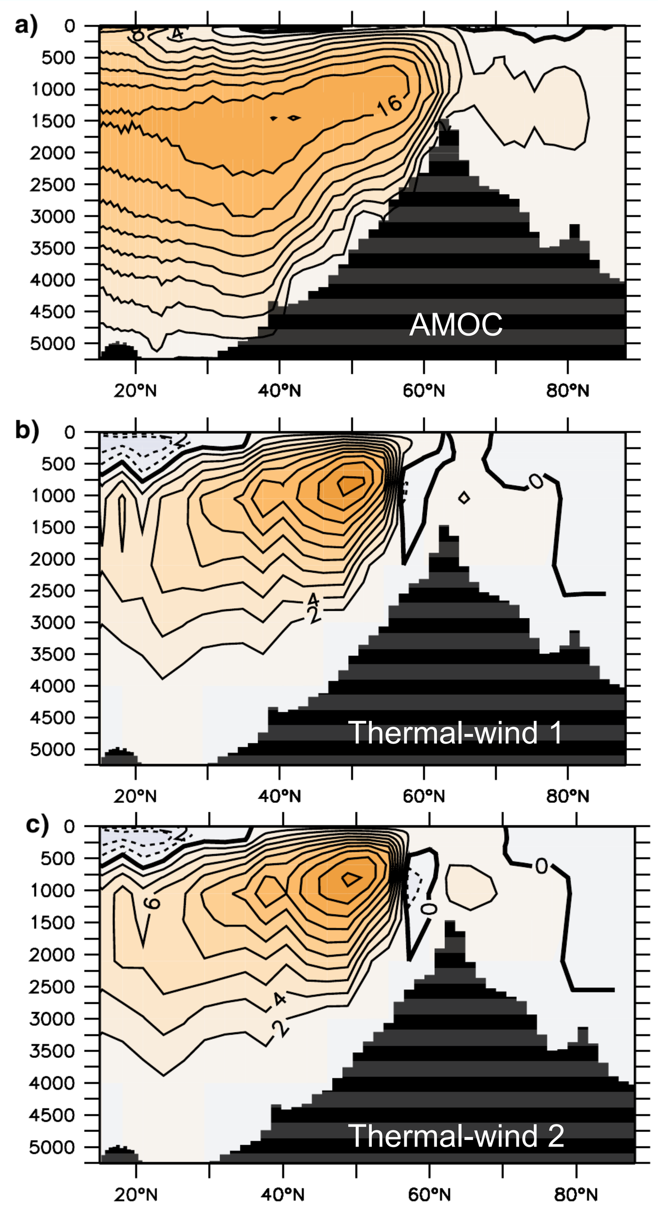


Fig. 7 (right) For the period 1000–1990 CE **(a)** AMOC (in Sv) and **(b–c)** thermal-wind transports, both calculated from zonal differences in coastal densities but applying different corrections to ensure mass conservation (Hirschi and Marotzke, 2007 for further details).

Fig. 8 (left) Strength of the AMOC and the thermal-wind transports, as in Fig. 4a.



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6. Take-home Messages

1) Both the simulated and pseudo-reconstructed FC show the same long-term variability over the past millennium and are closely linked to the AMOC strength variability. The FC therefore stands as a good indicator of past AMOC changes.

2) Whereas internal climate variability mainly drives the AMOC/FC variations during the preindustrial era, increasing GHG concentrations forces a weakening of both the FC and the AMOC during the industrial era. These features are well captured by the pseudo-reconstructed FC and, in particular, by its thermal component. The simulation, however, does not support the reconstructed minimum during LIA in the FC.

3) Both the North Atlantic circulation structure and its variability on multidecadal and longer timescales can be well reproduced from reconstructions based on coastal zonal density gradients alone.

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