NAO-Related Buoyancy Fluxes in the Labrador Sea as Sufficient Forcing for Atlantic Multidecadal Variability

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Background

- ✓ Multidecadal variability in the North Atlantic SST (AMV) is a robust phenomenon with significant impacts over the surrounding continents, but its mechanism is still under debate (*Ocean dynamics vs. stochastic atmospheric forcing vs. anthropogenic forcing*)[1,2].
- ✓ While the mechanism of *NAO-related buoyancy forcing → deep water formation → Atlantic meridional overturning circulation (AMOC) → AMV* has been put forward and found in some coupled simulations, it is based on statistical relationships and has not been proved in a explicit and controlled way in the coupled framework.
- ✓ **By designing coupled ensemble experiments that can test the above mechanism explicitly, we try to show that the mechanism is at work and NAO-related buoyancy fluxes are sufficient forcing for AMV and associated climate variability.**

Summary

- ✓ By imposing additional surface heat flux associated with the NAO *only* over the Labrador Sea in the coupled ensemble simulations, we find:
  - (1) **A canonical AMV pattern** associated with an AMOC increase and consequent heat convergence in the SPNA.
  - (2) An atmosphere response resembling negative NAO plays a critical role in developing and maintaining the shape of the simulated AMV.
  - (3) Associated with the evolution of the simulated AMV, we find a northward shift of the ITCZ, warmer/wetter western Europe, and warmer/drier southwestern US during summer, all previous reported as impacts of AMV.
- ✓ **NAO-related buoyancy fluxes in the Labrador Sea are sufficient forcing for AMV and associated climate variability.**

1. Experimental design

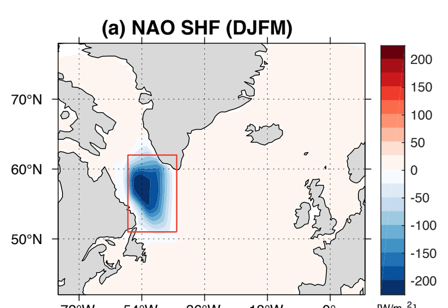
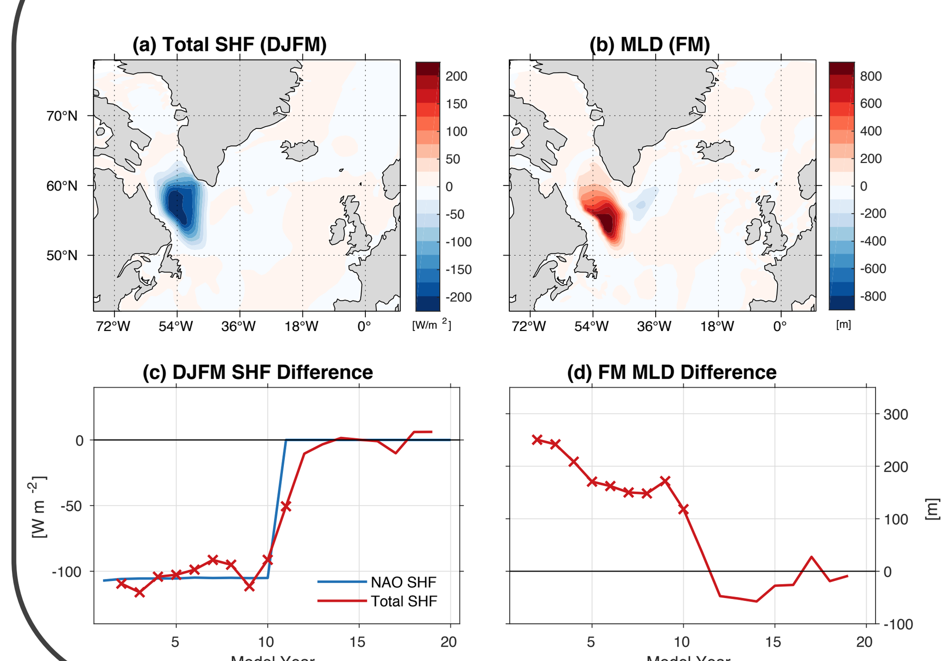


Fig. 1. Dec.-Mar. (DJFM) NAO-related heat flux forcing difference imposed in the ensemble simulations.

- Surface heat flux equivalent to the 3 standard deviation of the DJFM NAO (regression) is subtracted from (+NAO) or added to (–NAO) the ocean component of coupled ensemble simulations using CESM1, similar to ref 3, but only in the Labrador Sea (Fig. 1).
- The forcing is applied for 10 years during winter (DJFM), with a linear ramping up (down) from (to) mid-November (April).
- There are 10 ensemble members for each ±NAO case and each ensemble member runs another 10 years after the forcing stops (20 years in total).
- Otherwise, the coupled system freely evolves and interacts with each other in response to the forcing.
- 5-year running-averaged ensemble mean differences (+NAO – –NAO) are taken as the low-frequency responses of the coupled system to the NAO forcing.

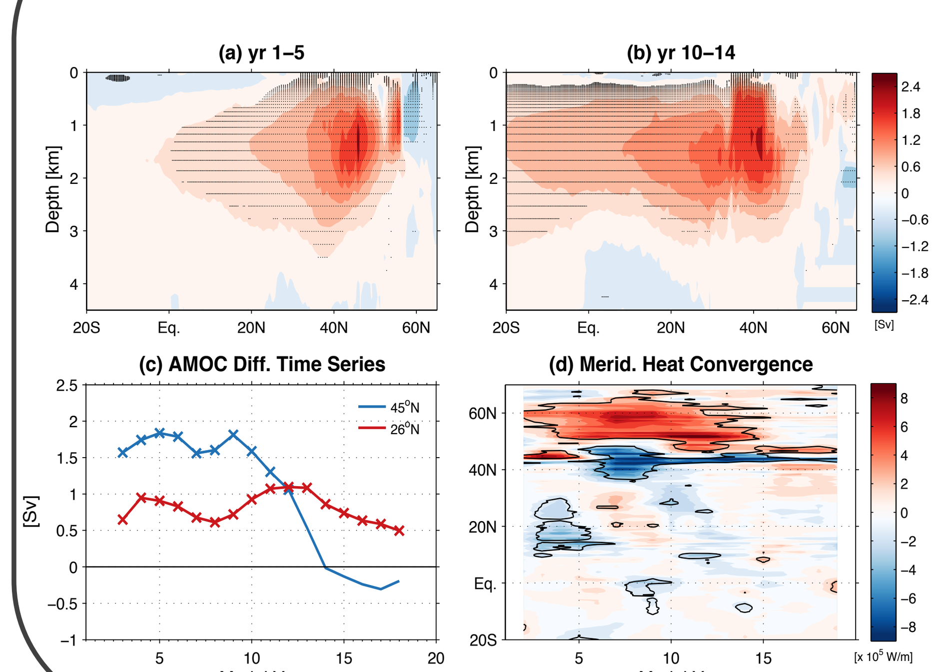
2. Labrador Sea response



- Total DJFM heat release is restricted to the Labrador Sea, and close to the imposed NAO forcing (Fig. 2a,c) → No significant heat flux forcing other than the imposed heat flux forcing.
- Mixed layer depth increases (~200 m in average; up to ~ 1000 m locally) only in the Labrador Sea (Fig. 2b), indicating enhanced deep water formation there, but rapidly return to a normal state once the forcing stops (Fig. 2d).

Fig. 2. (a-b) Ensemble mean DJFM total heat flux (a) and Feb.-Mar. mixed layer depth (MLD) (b) differences averaged over years 1-10 (forcing period). (c-d) 5-year running-averaged DJFM total heat flux and imposed NAO forcing (c) and FM MLD (d) difference time series averaged over the Labrador Sea (boxed in Fig. 1). Crosses indicate the statistically significant differences in (c-d).

3. AMOC/Northward heat transport response



- In response to the enhanced deep water formation in the Labrador Sea, basin-scale AMOC strengthens (up to ~2 Sv; Fig 3a-c).
- The AMOC increase is sustained even after the forcing stops (Fig 3c).
- Associated with the AMOC increase, heat convergence occurs in the subpolar North Atlantic (SPNA)[1], mostly in the upper 700 m (Fig 3d).

Fig. 3. (a-b) Ensemble mean AMOC streamfunction differences averaged over years 1-5 (a) and 10-14 (b). 5-year running-averaged ensemble mean (c) AMOC difference time series at 26° and 45°N and (d) meridional heat convergence difference hovmoller diagram. Stippled (a-b) and black-contoured (d) areas indicate the statistically significant differences.

4. Sea surface response

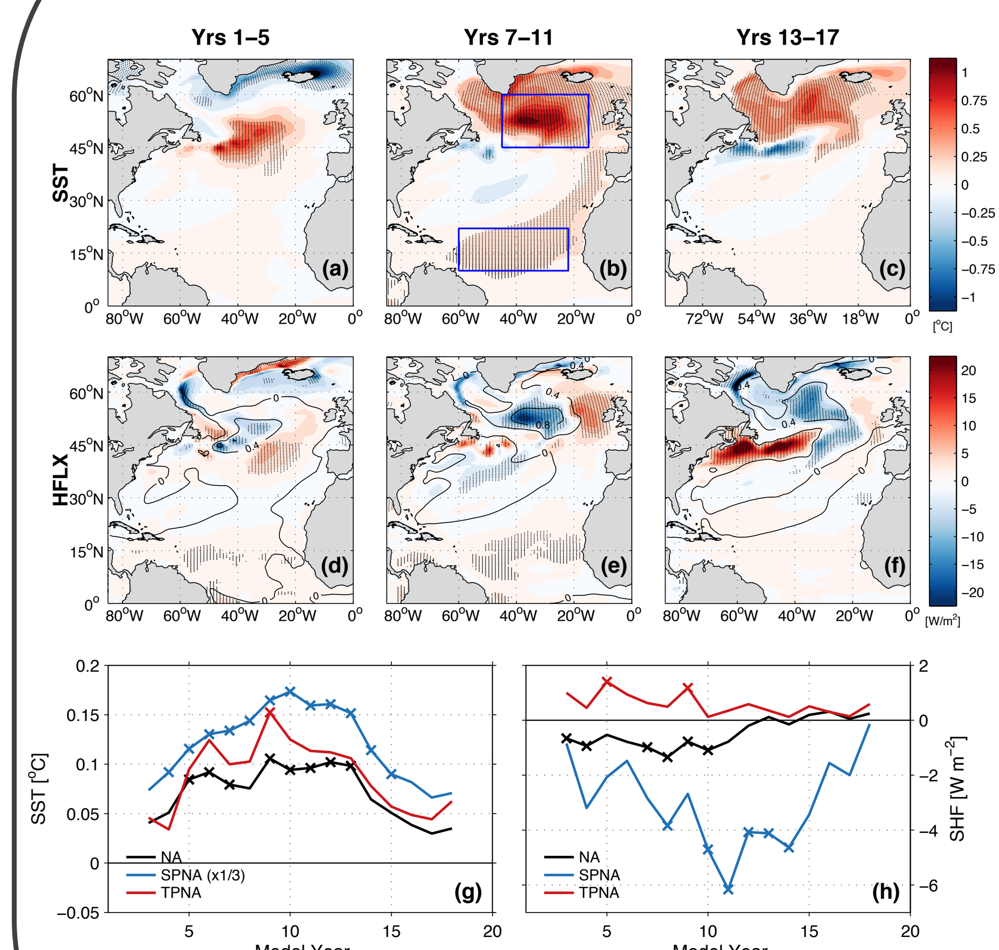
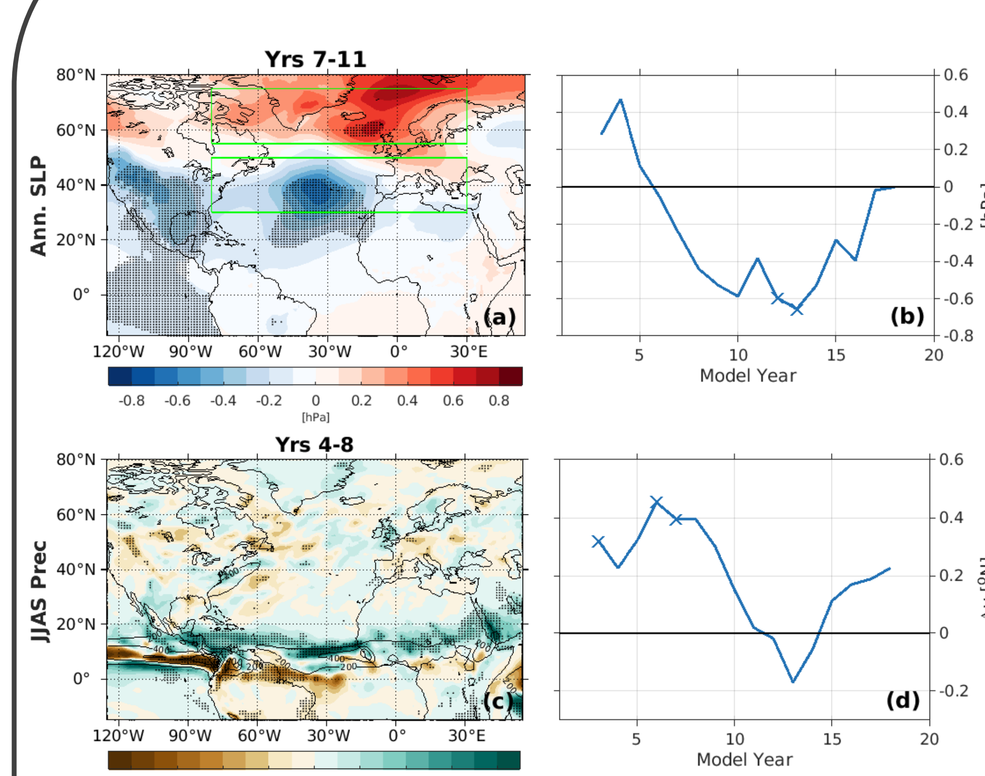


Fig. 4. Ensemble mean SST (a-c) and surface heat flux (SHF; d-f) differences averaged over years 1-5 (a,d), 7-11 (b,e), and 13-17 (c,f). The contours in (d-f) are as in (a-c) with contour intervals of 0.4°C. 5-year running-averaged ensemble mean entire NA, SPNA, tropical NA SST (g) and SHF (h) difference time series.

- SST first warms along the North Atlantic current (Fig. 4a), which penetrates into SPNA and the tropics/subtropics later, eventually forming a canonical AMV pattern (Fig. 4b), consistent with observations[2].
- The tropical extension is mostly generated by (turbulent) heat fluxes (Fig. 4e,h), confirming the importance of atmospheric teleconnection for the tropical signal[1,4].
- While heat is releasing at the core of the SPNA SST signal, confirming that it can be used as a signature of ocean dynamic driving AMV[5], it is also found that heat is going into the ocean in the area surrounding the core (Fig. 4e-f).
- The above two bullets are due to a negative NAO-like response in the atmosphere (see Fig. 5a-b), suggesting the atmosphere response is essential in shaping the canonical AMV pattern.

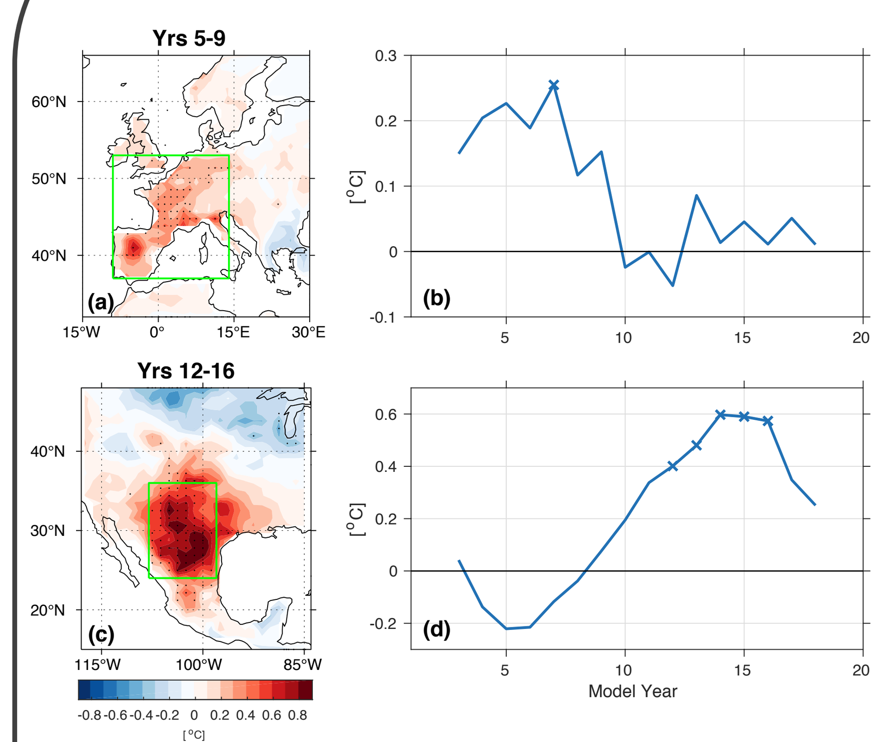
5. Large-scale atmosphere response



- A negative NAO-like atmosphere response[1] (Fig. 5a) develops and persists along with the SST signal (Fig. 5b).
- This SLP pattern corresponds to weakened subpolar westerlies and trades winds, consistent with the (turbulent) heat flux response (Fig. 4e).
- A northward shift of the ITCZ and associated Sahel rainfall increase[1] is evident (Fig. 5c).
- This ITCZ response peaks early before the peak of the tropical SST signal, suggesting a fast response to the SPNA SST rather than the tropical SST[6], and rapidly moves back to the climatological position (Fig. 5d).

Fig. 5. Ensemble mean annual SLP (a) and Jun.-Sep. (JJAS) precipitation (c) differences averaged over years 7-11 and 4-8, respectively. The climatological JJAS precipitation from the control simulation is also shown in contours in (c). 5-year running-averaged ensemble mean pressure difference time series between two boxes (b) indicated in (a) (north minus south) and maximum zonally averaged (80°W-40°E) JJAS precipitation latitude difference time series relative to the climatological position (d).

6. Regional response over land



- Warmer and wetter (not shown) conditions during summer are found in western Europe[1] (Fig. 6a), but before the peak of the simulated AMV (Fig. 6b).
- This is possibly because of the weak westerlies (–NAO) in the later years (Fig. 5a-b).
- Warmer and drier (not shown) summer conditions are also found in the central southern US/northern Mexico[1,7] (Fig. 6c), but after the peak of the simulated AMV (*Fig. 6d*).
- This is possibly related to a late development of a low pressure in this region[7] (Fig. 5a).

Fig. 6. Ensemble mean annual JJAS surface air temperature (Ts) differences in the Europe (a) and southwestern North America averaged over years 5-9 and 12-16, respectively. 5-year running-averaged ensemble mean JJAS Ts difference time series averaged over the western Europe (boxed region in (a)) (b) and southern North America (boxed region in (c)) (d).

6. Discussion

- The 3 SD NAO heat flux forcing is quite extreme, but in nature, the total NAO buoyancy forcing also comes with freshwater forcing due to net evaporation, and the same sign of NAO-related buoyancy forcing takes place in the entire SPNA, which can trigger local deep water formation (e.g., Irminger Sea) or eventually contribute to buoyancy changes in the Labrador Sea.
- The importance of the atmosphere response for the AMV pattern outside of the SPNA SST core suggests that simulated AMV patterns can be different, depending on the strength and location of the atmospheric response, in individual models.
- The tropical SST signal is weak and short-lived relative to observations, which is commonly found in coupled models[1]. In our experiment, it is mostly associated with turbulent heat fluxes associated with atmospheric circulation change (–NAO), but some previous studies have suggested that it could develop through radiative forcing due to cloud cover and dust input changes[1,4].
- While most studies can find the climate impacts of AMV at zero lag because of a long-term averaging, which blurs lead-lag relationships, we find that some of the climate impacts take place with some lags. The lead-lag relationships may be important in order to understand the mechanisms of AMV's climate impacts.
- We have performed additional ensemble experiments with 5 year forcing of 2 and 3 SD cases and found that for the generation of the basin-scale AMV shape (tropical part), a sustained NAO forcing is important.

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