More positive North Atlantic Oscillation cools the subpolar North Atlantic in the past century

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Abstract

Sea surface temperature (SST) in the subpolar North Atlantic has significantly decreased at a rate of -0.39 (±0.23) K/century during 1900–2020, which runs counter to global warming due to anthropogenic forcing. The cooling in the subpolar North Atlantic, known as the North Atlantic cold blob, could be driven by a host of mechanisms involving both the ocean and the atmosphere. Here, we present evidence that changes in the atmospheric circulation over the North Atlantic, in particular a centennial trend towards a more positive phase of the North Atlantic Oscillation (NAO), could have contributed to the cold blob. The positive NAO intensifies the surface wind over the subpolar North Atlantic and induces excessive heat loss from the air-sea interface. According to an idealized mixed layer heat balance model, the NAO-induced heat loss alone cools the subpolar North Atlantic by 0.26 K/century, which explains 67% of the observed cold blob SST trend. Thus, besides ocean circulation changes, including the slowdown of the Atlantic Meridional Overturning Circulation, the large-scale atmospheric circulation might have played an equally important role in promoting the century-long SST changes in the subpolar North Atlantic.

Introduction

In contrast to global surface warming, the SST in the center of the North Atlantic subpolar gyre has cooled by about -0.4 K/century, a phenomenon known as the North Atlantic "cold blob".

The cold blob has been widely accepted as a result of decreased meridional oceanic heat transport due to weakened Atlantic Meridional Overturning Circulation (AMOC)[1,] but observational records remain short to constrain the long-term AMOC change. Meanwhile, a host of mechanisms can drive the low-frequency SST variability, and the NACB could result from gyre circulation change[2] and more storminess[3].

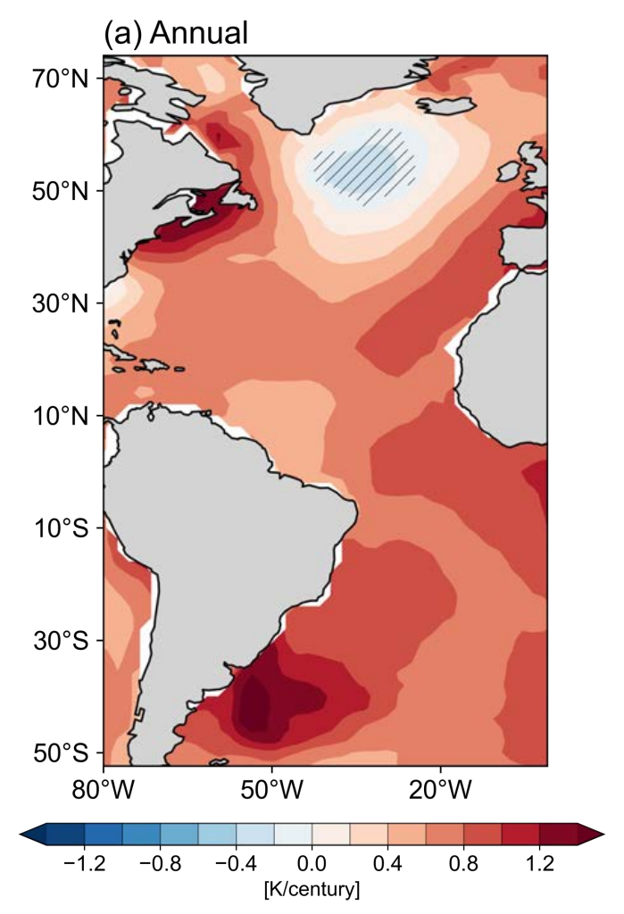


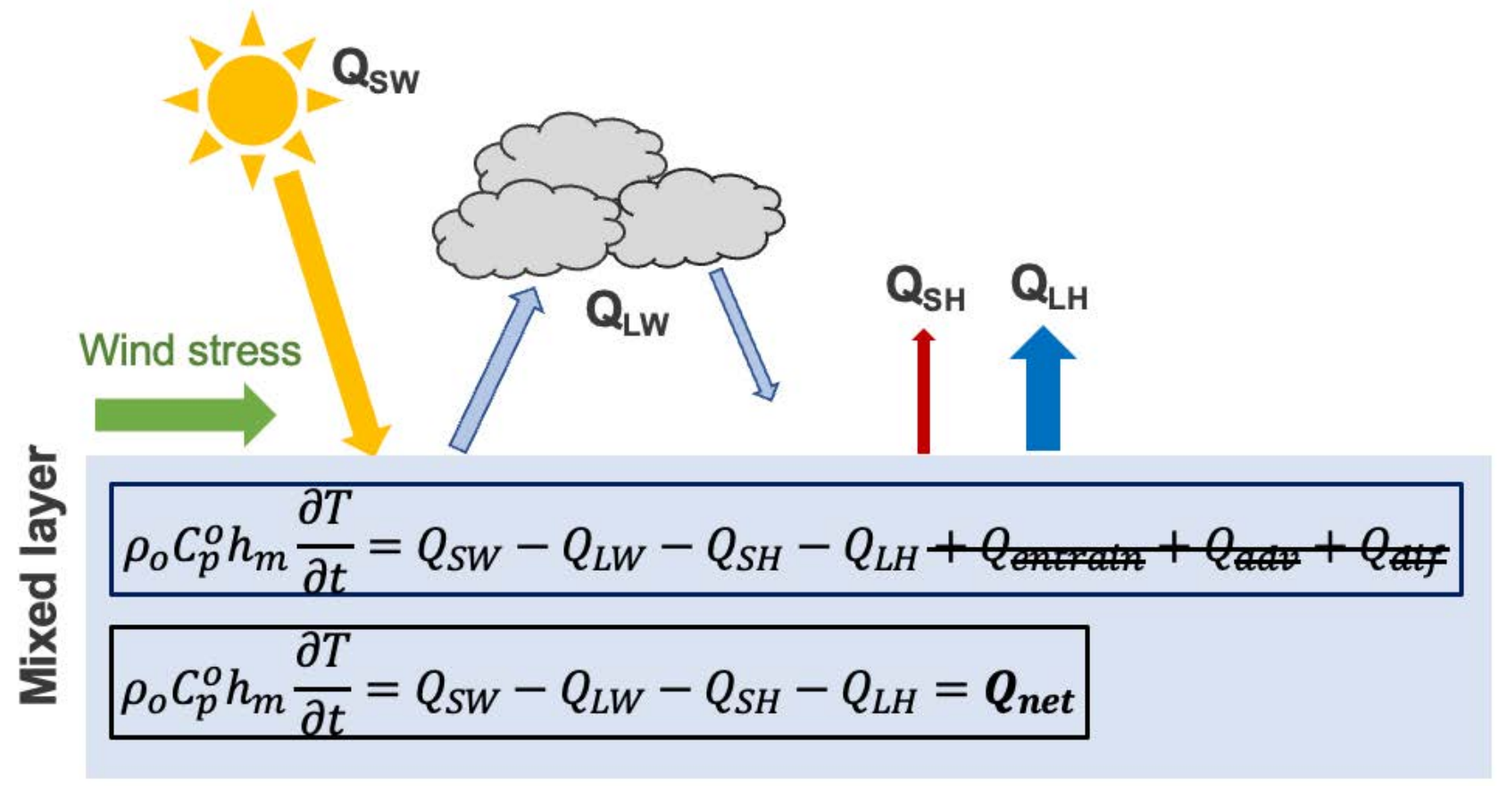
Fig.1: Annual mean SSTA trends over 1900–2019, based on the averages of five observational datasets (HadISST, ERSSTv4, ERSSTv5, COBE-SST2, and Kaplan). Hatched is where the five datasets show disagreement on the sign of the trend.

The atmospheric circulations have undergone substantial changes over the North Atlantic. Changing atmospheric circulation could prompt/inhibit sea-to-air heat loss by enhancing/weakening surface winds. However, how and to what extent the atmospheric circulation change has contributed to the cold blob remains unknown.

This study hence uses an idealized one-dimensional mixed-layer heat balance model to quantify the direct thermal contributions of atmospheric circulation to the cold blob.

Method

- Mixed layer heat balance, ignoring oceanic processes:



$$\rho_o C_p^o h_m \frac{\partial T}{\partial t} = Q_{SW} - Q_{LW} - Q_{SH} - Q_{LH} \cancel{+ Q_{entrain}} \cancel{+ Q_{adv}} \cancel{+ Q_{dif}}$$

$$\rho_o C_p^o h_m \frac{\partial T}{\partial t} = Q_{SW} - Q_{LW} - Q_{SH} - Q_{LH} = \boldsymbol{Q_{net}}$$

- The net air-sea heat flux anomaly includes a forcing mechanism and a damping mechanism:

$$Q'_{net} = \underbrace{-\alpha T'}_{\text{damping}} + \underbrace{Q'_{atmo}}_{\text{forcing}}$$

**Derivation of the damping coefficient is described in detail by Li et al. (2020)[4]*

- Atmospheric forcing, Q'_{atmo}, is parameterized as a linear combination of atmospheric circulation modes and white noise:

$$Q'_{atmo} = \beta_1 PC_1 + \beta_2 PC_2 + \beta_3 PC_3 + N(0, \sigma^2)$$

Results

(1) Atmospheric circulation changes

The 20th century has seen changes in atmospheric circulation over the North Atlantic, including a more positive NAO, an amplification of NAO mode variance, and a reduction of the EAP variance.

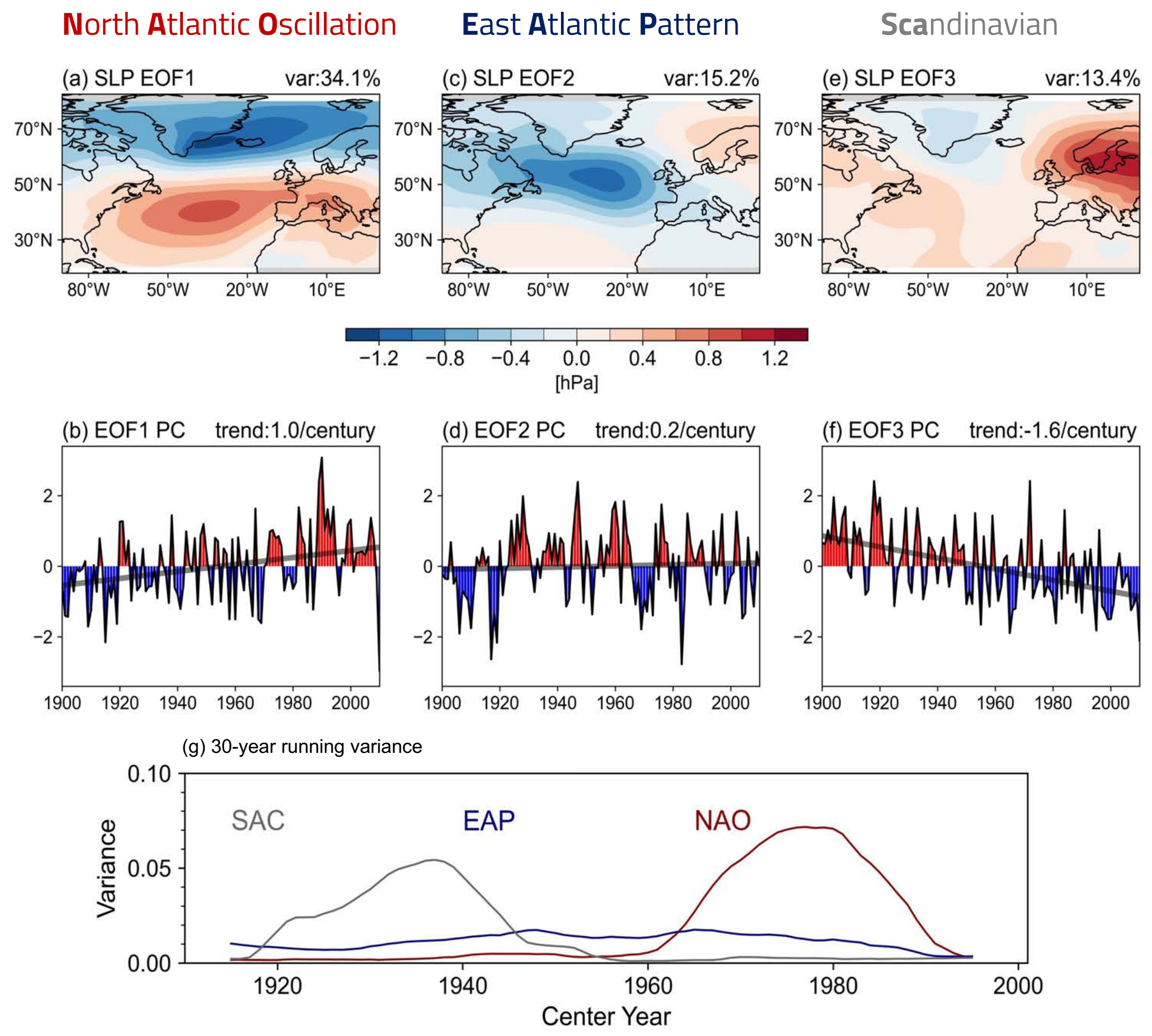


Fig.2: **(a)–(f)** The first three EOF modes of annual mean North Atlantic sea level pressure (SLP) in ECMWF 20th-century reanalysis. PC time series is scaled by the standard deviation. Trends of EOF1 PC and EOF3 PC are statistically significant (p<0.05). **(g)** Temporal change of explained variance of the three modes of variability with a 30-year running window.

(2) Corresponding atmospheric forcing changes

Surface wind speed is primarily responsible for the $\mathrm{Q}_{\mathrm{atmo}}$ patterns associated with the three atmospheric modes of variability, while the contributions of near-surface air temperature are regional and an order of magnitude smaller.

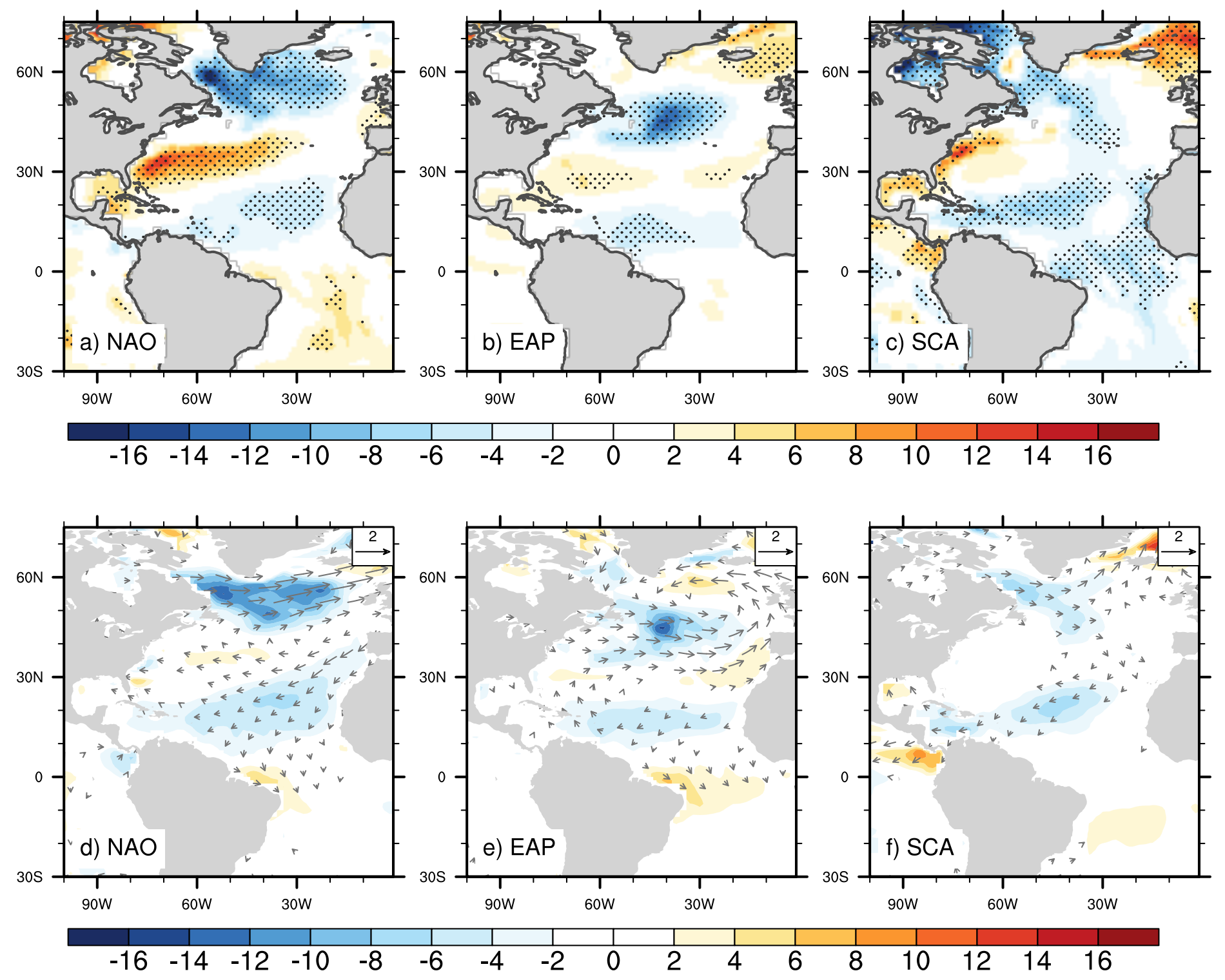


Fig.3: **(a)–(c)** The $\mathrm{Q}_{\mathrm{atmo}}$ regressed upon SLP PCs (shaded; unit: Wm^{-2}) of NAO, EAP, and SCA. Stippled grid points are where the regression coefficients are statistically significant at a 0.01 level. **(d)–(f)** Regressed $\mathrm{Q}_{\mathrm{atmo}}$ that is caused by surface wind speed change. The arrows in d)-f) are the anomalous surface wind (vector, unit: $\mathrm{m\,s^{-1}}$) composite on the PCs. Air-sea heat fluxes are from 20CR v2, NCEP/NCAR, and ERA-5 reanalysis datasets.

(3) Surface temperature responses

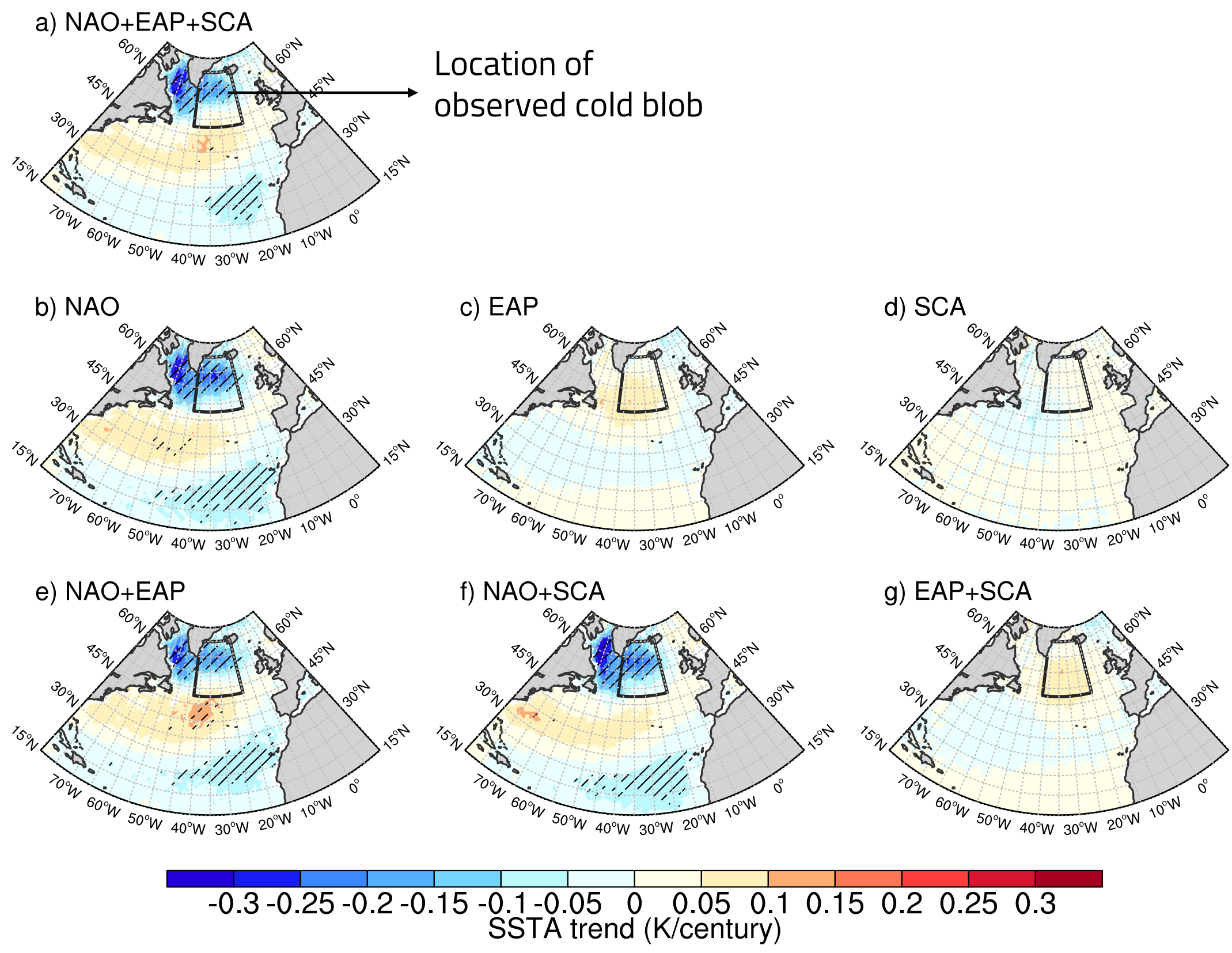


Fig.4: The SSTA trend forced by the changes in atmospheric modes of variability in the 1900–2017 period based on the simulations by the stochastic model. In the idealized model simulation, Q_{atmo} is parameterized as the combination of **(a)** NAO, EAP, and SCA, **(b)** NAO, **(c)** EAP, **(d)** SCA, **(e)** NAO and EAP, **(f)** NAO and SCA, **(g)** EAP and SCA. Each set of simulations consists of 1000 randomized runs. Grid cells with 95% of the runs agreeing on the sign of the trend are hatched.

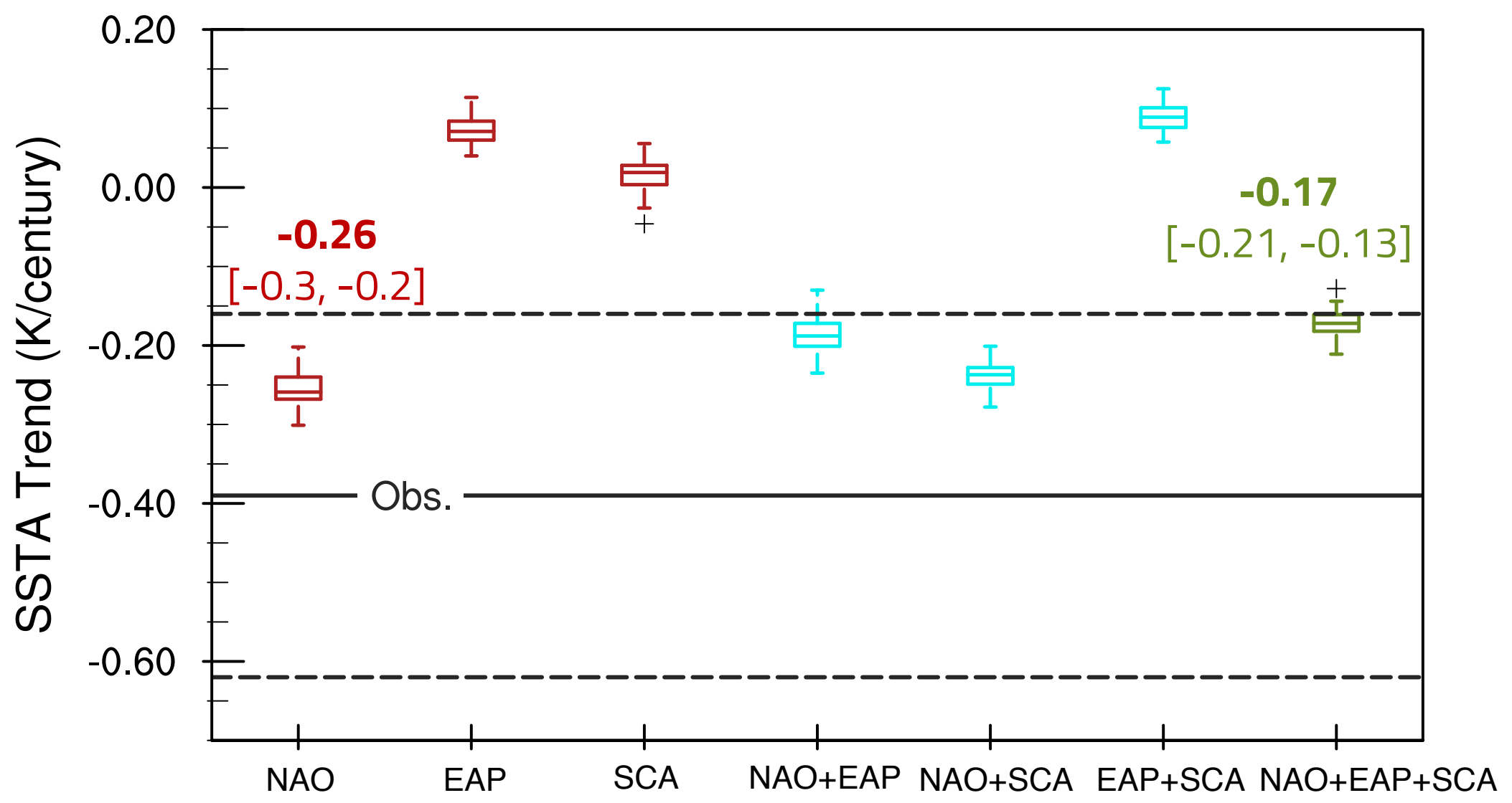


Fig.5: The Box-and-whisker plot of SSTA trend averaged over the cold blob region. Each box corresponds to the stochastic model simulations with Q_{atmo} parameterized as linear functions of atmospheric modes of variability. The uncertainty range of the simulated SSTA is quantified by repeating the simulation 1000 times. The boxes represent the interquartile range and the horizontal lines within the boxes represent the median of the simulated SSTA trend.

Conclusion

The 20th-century North Atlantic atmospheric circulation has seen a trend towards a more positive NAO with increased variance.

Quantified by a stochastic model, changes in the atmospheric modes of variability could have contributed 44% (-0.17 K/century) of the observed cooling trend of the Irminger Sea SST.

A more positive NAO is a primary contributor to the forced subpolar cooling, primarily through the intensification of the jet stream and the wind over the North Atlantic storm track. This cooling effect is marginally offset by the changes in the EAP and SCA.

This study suggests a potential role of atmospheric circulation in forcing the North Atlantic cold blob. Meanwhile, the SSTA cooling trend unexplained by the atmospheric circulation suggests oceanic processes are indispensable.

Acknowledgements

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