Characterizing Atmospheric Variability in Large Ensemble Simulations with Machine Learning

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Introduction

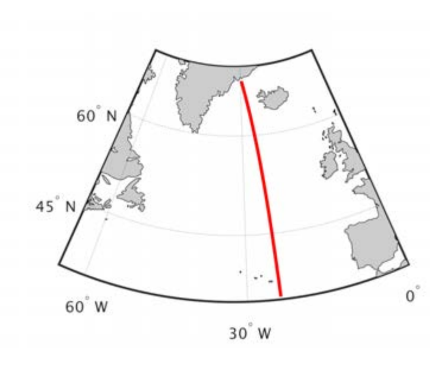
- The North Atlantic Warming hole (NAWH) is a region in the subpolar gyre where there is a deficit in projected SST increase caused by a reduction in deep water formation and slowdown of the AMOC [1,2,3,4]
- There are two dominant mechanisms responsible for the seasonal atmospheric response to the NAWH found in Gervais et al. 2019
  1. A direct response consistent with the atmospheric response to a low level cooling as described by Hoskins et al. 1981 consisting of a negative temperature anomaly that reduces with height, a local high pressure anomaly downstream, and a baroclinic response in the geopotential height fields
  2. A transient eddy-mean feedback response where the enhanced SST gradient causes increased baroclinic eddy energy that propagates vertically and horizontally and causes a strengthening of the North Atlantic jet
- This study will employ the same model experiments as Gervais et al. 2019 but will focus on the impact of the NAWH on atmospheric variability
- We will use self-organizing maps, a machine learning method, to identify dominant patterns of variability and show how this method can be used to ascertain differences in variability between sets of large-ensemble simulations.

Model Set-up

- Large ensemble Community Atmosphere Model 5 (CAM5) atmosphere-only simulations with 25 members.
- Simulations are branched from and prescribe corresponding SSTs and sea ice from individual individual Community Earth System Model Large Ensemble [6] ensemble members
- Two seasonally varying fill patches are produced to represent the magnitude of the NAWH's deficit in warming by taking the differences between the 2050's (2090's) decadal average and a 1K (2K) threshold
- Set of 7 experiments are conducted where each day of SSTs are altered by adding these fill patches to either "fill" or "deepen" the warming hole

Experiment Name	SST Modification	Time Interval
CNTRL10	N/A	2006-2019
CNTRL50	N/A	2046-2059
CNTRL90	N/A	2086-2099
1KFill50	+1K Fill	2046-2059
2XDeep50	-1K Fill	2046-2059
2KFill90	+2K Fill	2086-2099
2XDeep90	-2K Fill	2086-2099

Table 1: Description of model simulations



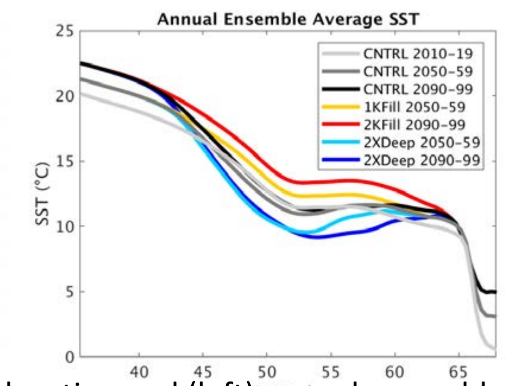


Fig. 1: (right) Cross section location and (left) annual ensemble average SST for each experiment through cross section. [5]

Self-Organizing Maps Analysis

- SOM is a machine learning method that produces a set of archetypal patterns (SOM nodes) through iterative training that represent the dominant variability in a dataset
- The SOM method is used to classify dynamic tropopause wind speed (DT wind) output from all experiments into a 3x4 set of SOM node patterns or "regimes"
- Best match unit frequencies (BMUF) provide information about how often each map occurs and composites of days associated with each map node are conducted to examine multiple meteorological fields associated with each map node
- The total difference between two experiments can be approximated as the sum over all SOM map nodes of the frequency of occurrence of each node (f_i) multiplied by its SOM node composite (S_i) for that field
- We can further decompose this $\Delta(fS)$ into the role of differences in frequency (Δf) and the role of differences in SOM node composite (ΔS)

$$\Delta(fS) = \Delta f S_{avg} + \mathrm{f_{avg}}\Delta\mathrm{S},$$

$$\text{where} \quad \Delta f S_{avg} = \sum_{i=1}^{n}(f_{1i} - f_{2i})\frac{S_{1i}+S_{2i}}{2} \quad \text{and} \quad f_{avg}\Delta S = \sum_{i=1}^{n}\frac{f_{1i}+f_{2i}}{2}(S_{1i} - S_{2i})$$

SOM Node Composites

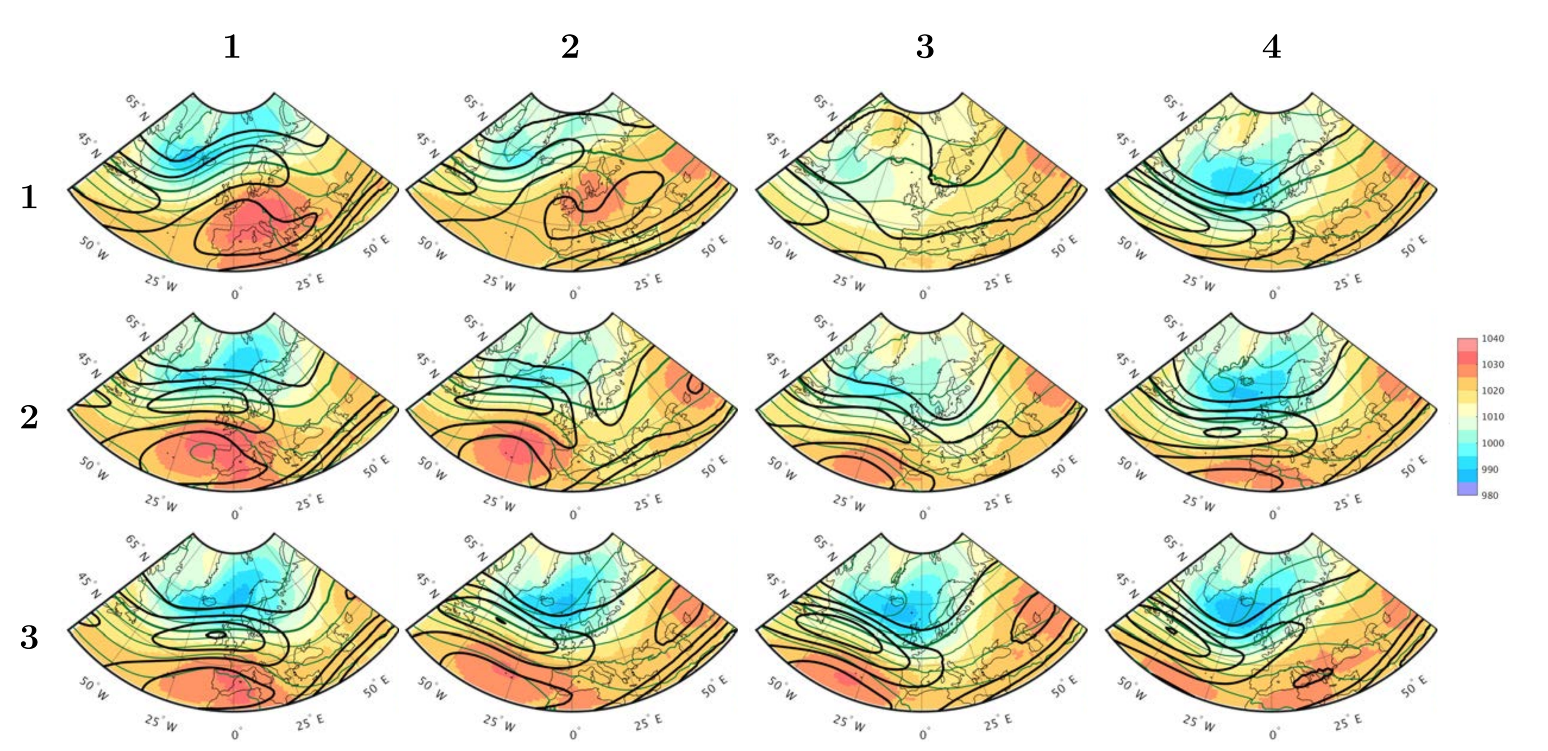


Fig. 2: SOM map node composites for all experiments with wind speed on the dynamic tropopause in black contours every 10m/s beginning at 20m/s, sea level pressure (hPa) in color, and 500hPa geopotential height in green contours every 100m with the 5400m contour in bold.

- The SOM method is used to classify DT wind variability in our experiments into a series of SOM map node patterns, which we will also refer to as "regimes" (Fig. 2)
- For CNTRL10 the most frequent regime is node (1,1) at 10.2% and least frequent node (2,4) at 6.4% (Fig. 3a)
- As the century progresses without the development of the NAWH (Fig. 3a-c) regimes with weaker poleward shifted jets become less common (Nodes (1,1),(1,2),(2,1),(2,2)) and those with stronger equatorward shifted jets (Nodes (1,4),(2,3),(2,4)), as well as Node (3,1) with a stronger more poleward jet become more common

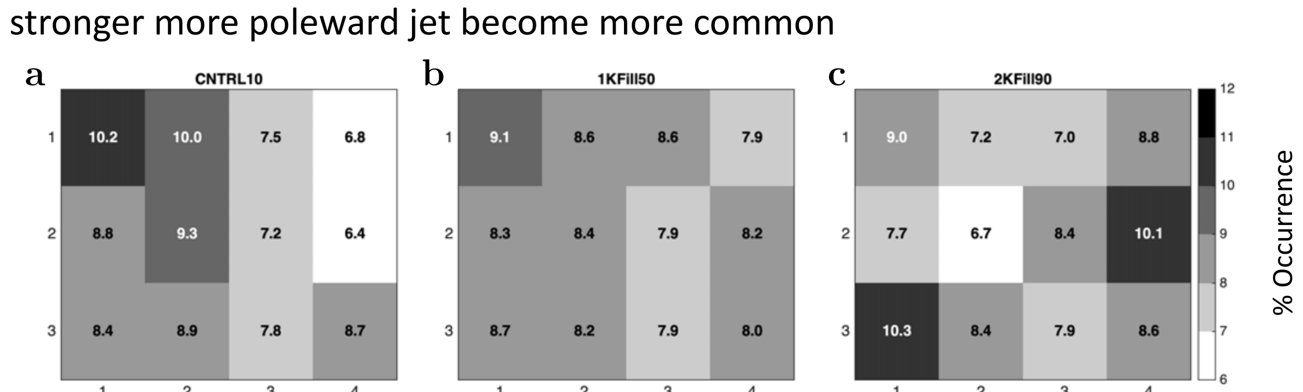


Fig. 3: Best match unit frequencies for each of the 12 SOM nodes for the CNTRL10, 1KFill50, and 2KFill90 experiments

CNTRL90-2KFill90 - ΔS and Δf

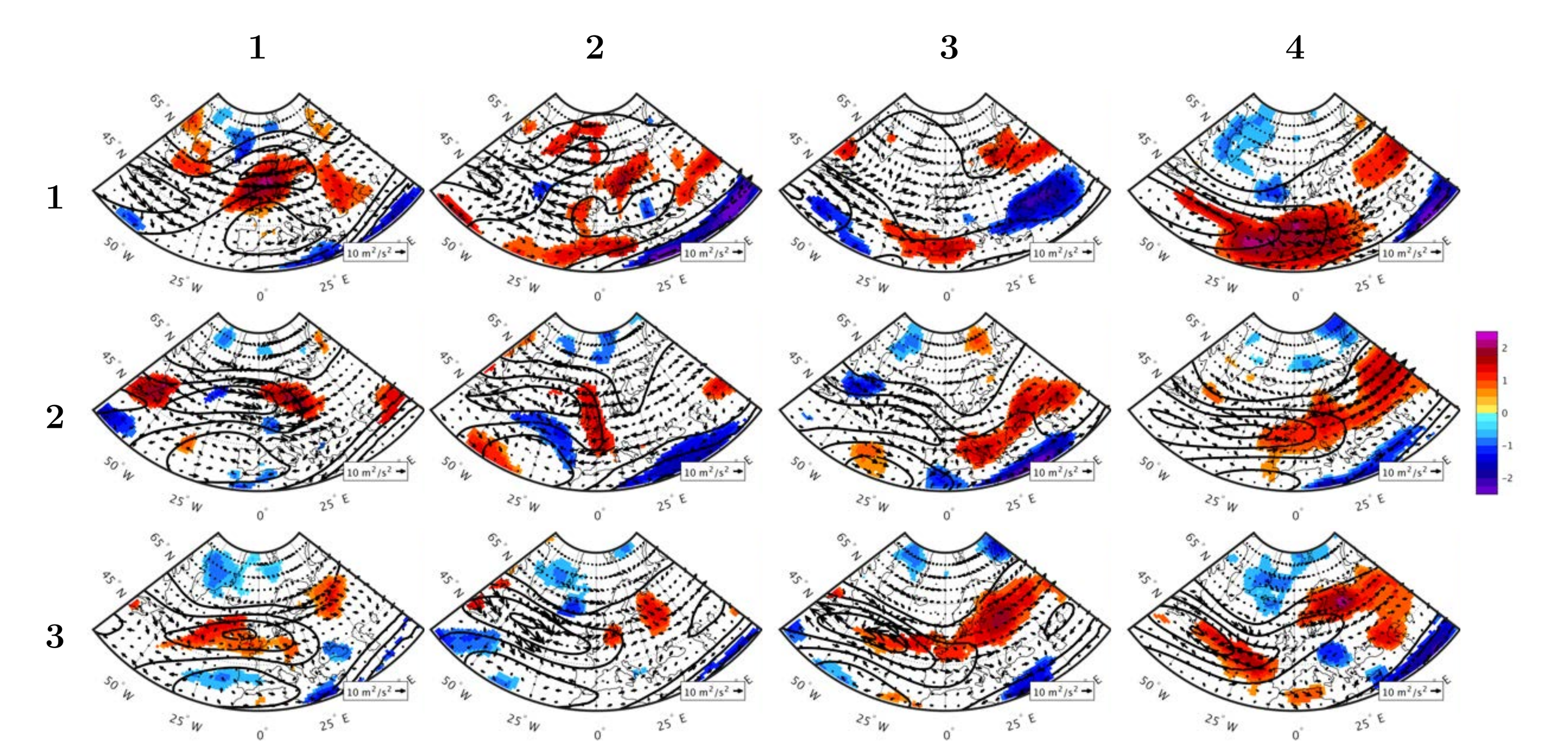


Fig. 4: ΔS between CNTRL90-2KFill90 experiments for dynamic tropopause wind speed (m/s, color significant at 95% confidence level as per a 2-sided student's t-test) and horizontal E-vector at 200hPa (m^2/s^2, vector). The average dynamic tropopause wind speed for the two experiments are shown in contours every 10m/s beginning at 20m/s.

- ΔS for CTNRL90-2KFill90 generally shows extensions of the North Atlantic jet that occur at different longitudes depending on where the jet terminates in a given regime.
- Δf for CNTRL90-2KFill90 are characterized by an increase in frequency of patterns on the right side of the map with stronger North Atlantic jets. Note: for other experiment differences, the NAWH leads to increase in row 3 vs. row 1 regimes

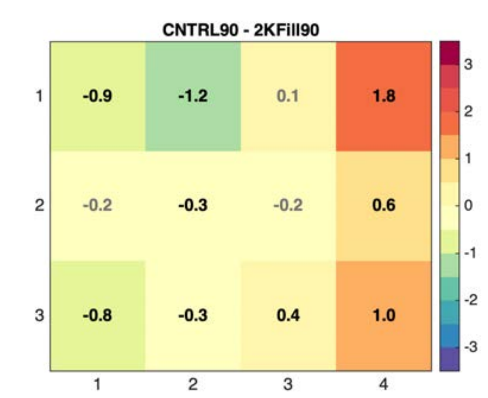


Fig. 5: Δf between CNTRL90-2KFill90 with significant differences in bold computed using a permutation test.

References and Acknowledgements

[1] Rahmstorf, S., et al. Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nat. Clim. Chg. , 5, 1–6 (2015)
[2] Drijfhout, S., et al. Is a decline of AMOC causing the warming hole above the North Atlantic in observed and modeled warming patterns?, J. Clim., 25 , 8373–8379 (2012)
[3] Gervais, M., et al. Mechanisms Governing the Development of the North Atlantic Warming Hole in the CESM-LE Future Climate Simulations, J. Clim., (2018)
[4] Menary, M. B., & Wood, R. A. (2018). An anatomy of the projected North Atlantic warming hole in CMIP5 models. Climate Dynamics, 50 (7-8), 3063–3080.
[5] Gervais, M., Shaman, J., & Kushnir, Y. (2019). Impacts of the North Atlantic warming hole in future climate projections: Mean atmospheric circulation and the North Atlantic jet. Journal of Climate, 32 (10), 2673–2689.
[6] Hoskins, B. J., and D. J. Karoly, The Steady Linear Response of a Spherical Atmosphere to Thermal and Orographic Forcing. 1179–1196 pp. (1981)
[7] Kay, J. et al. The Community Earth System Model (CESM) Large Ensemble Project: A Community Resource for Studying Climate Change in the Presence of Internal Climate Variability, Bull. Amer. Meteor. Soc., 96, 1333–1349 (2015)
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CNTRL90–2KFill90 $\Delta(fS), \Delta f S_{avg}, f_{avg}\Delta S$

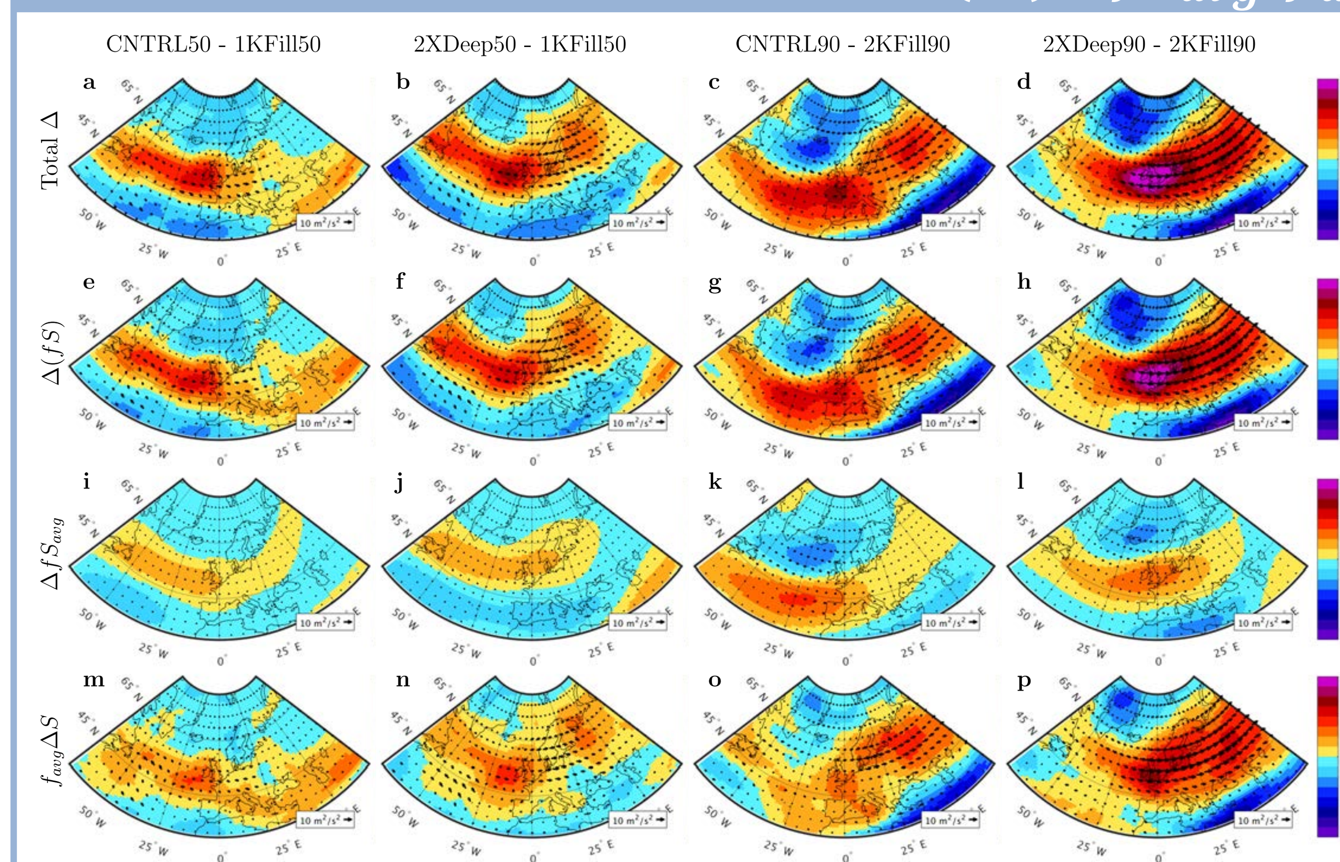

Fig. 6: Decomposition of experimental differences into impact of frequency and SOM map node composite for DT Wind (color,m/s²) and E_{h200} (vectors, m^2/s^2). Total difference (a,b,c,d), $\Delta(fS)$ (e,f,g,h), $\Delta f S_{avg}$ (i,j,k,l), $f_{avg}\Delta S$ (m,n,o,p) for the CNTRL50-1KFill50 (a,e,i,m), 2XDeep50-1KFill50 (b,f,j,n), CNTRL90-2KFill90 (c,g,k,o), and 2XDeep90-2KFill90 (d,h,l,p) experiment differences.

- The decomposition of the total change (Fig. 6a-d) into $\Delta(fS)$(Fig. 6e-h) represents nearly the entirety of the seasonal mean differences
- Differences in DT Wind occur both as a result of Δf and ΔS with ΔS being more important
- The impact of ΔS is associated with the transient eddy forcing response occurring further downstream over Eurasia

Conclusion

- Self-organizing maps are used to identify regimes of North Atlantic jet variability within a set of large ensemble experiments
- The NAWH increases the frequency of occurrence of poleward shifted jets regimes
- The transient eddy-mean forced response to the NAWH also modifies the jet regimes themselves by increasing wind speeds within the jet over the North Atlantic and downstream over Eurasia. This response occurs at different latitudes, strengths, and orientations depending on the jet regime, similar to the dependence of the impact of midlatitude SST gradients on the mean jet location.
- Decomposition of the total seasonal differences between simulations into the role of changes in frequency vs. changes in SOM node composite reveals the importance of changes in the character of the jet itself.
- This analysis highlights that when a dimension reduction is conducted it is important to not only look the mode strength or frequency of occurrence but also at changes in the mode of variability itself.