EGU 2017
X4.6

Assessing variability in the size and strength of the North Atlantic subpolar gyre

Nick Foukal, Susan Lozier
Duke University, Nicholas.Foukal@Duke.edu

1. Introduction

Motivation:

Does the expansion/contraction of the subpolar gyre (SPG) control the amount of inter-gyre throughput from the subtropical gyre (STG) to the SPG?

Background:

Wind-driven Ekman divergence in the subpolar North Atlantic leads to a bowl-shaped mean sea-surface height (SSH) field (**Fig. 1a**), which in turn drives a cyclonic geostrophic SPG around a minimum SSH. Empirical Orthogonal Function (EOF) analyses of the North Atlantic SSH have indicated that the center of the gyre is rising faster than its boundary, flattening the SPG bowl and causing the gyre to decline (18-25% per decade since 1993).[1] The size and strength of the SPG are hypothesized to control the strength of the upper-layer connection between the STG and the SPG by allowing more STG water to flow northwards when the SPG is small (**Fig. 1b**).[1,2,3] In contrast, concurrent in situ observations of the SPG circulation (in the Labrador Current at 53°N, in the East Greenland Current at the OVIDE line and ARGO/PALACE floats) report either no trend or a slight decline in the gyre.[4,5,6]

Scope of this work:

In this work, we attempt to reconcile these conflicting assessments of the SPG size/strength as well as review the connection between the SPG size/strength and the magnitude of the inter-gyre throughput.

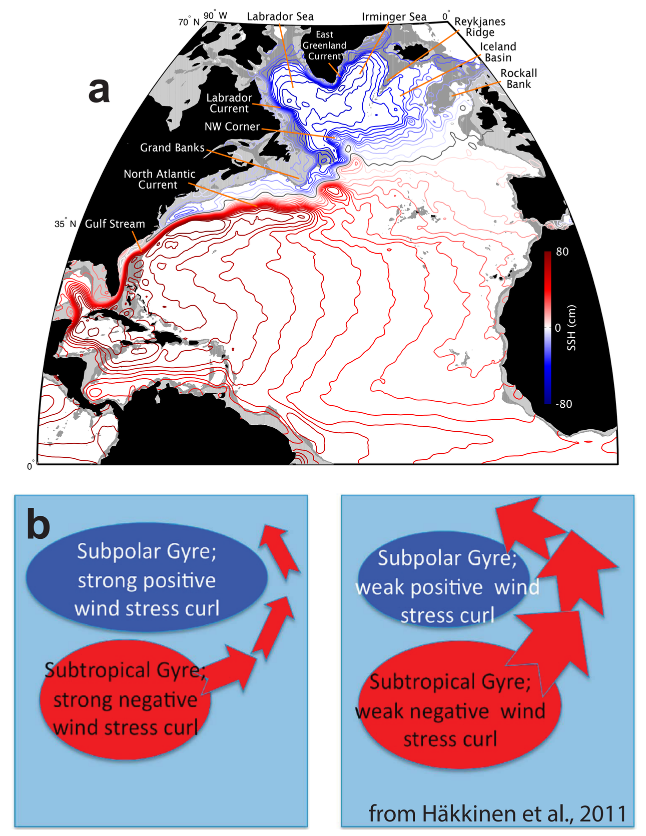

Figure 1. Time-mean satellite SSH field with locations of interest shown for reference (**a**). Cartoon depicting the conceptual model of the SPG size/strength influencing inter-gyre throughput (**b**). As the gyre declines due to weak positive wind stress curl, more STG water is able to flow northwards, warming the SPG.

2. Data and Methods

- North Atlantic SSH data: gridded absolute dynamic topography fields from AVISO, 1/4° x 1/4° (90°W-0°W, 0°N-70°), monthly (Jan. 1993 - Sep. 2015). EOF analysis done on 1°x1° resolution SSH data for consistency with previous studies.
- Wind stress curl (WSC) calculated from u,v wind vectors NCEP/NCAR Reanalysis (winters 1993-2015)
- North Atlantic Oscillation (NAO) from the Hurrell station-based NAO winter (DJFM) time series
- East Atlantic (EA) pattern time series from the NOAA Climate Prediction Center and averaged into winter (DJFM) values.
- Definitions for the new index (**Fig. 5**) at monthly 1/4° resolution:
  - SPG boundary = largest closed contour of SSH (contours drawn at 1 cm intervals)
  - SPG area = geographic area enclosed by SPG boundary
  - SPG center = minimum SSH within SPG boundary and north of 53°N
  - SPG strength = $SSH_{boundary}$ - SSH_{center} (an estimate of the barotropic mode in SPG strength)

3. Results

3.1 North Atlantic sea-level rise

Spatially-averaged North Atlantic SSH for comparison to EOF analysis (section 3.2)

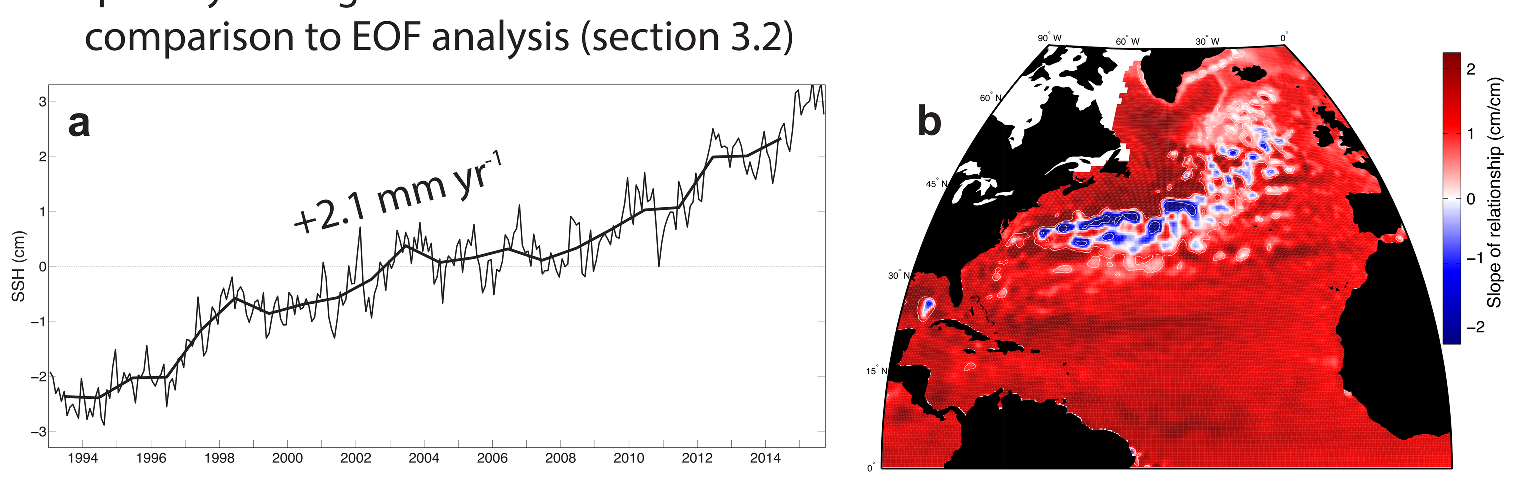

Figure 2. The basin-averaged SSH has increased by 2.1 mm/yr since 1993 (**a**) and weights almost coherently positively over the entire North Atlantic (**b**). The time series and spatial pattern are nearly mirror images of the Gyre Index (**Fig. 3a, b**). The cause of this sea-level rise is a combination of thermosteric and halosteric effects, melting of land ice, convergences of oceanic transport and changes to the hydrological cycle.[7]

3.2 EOF analysis of North Atlantic SSH

Non-Detrended

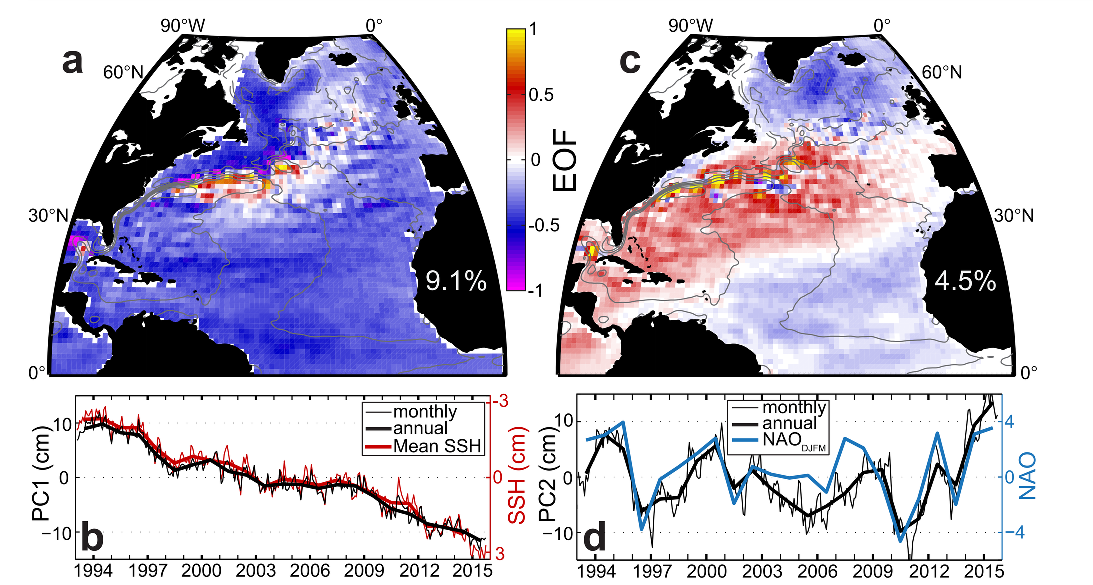

Figure 3. The leading mode of North Atlantic SSH (**a**,**b**) is defined to be the Gyre Index. The time series of the basin-averaged SSH (**b**, red, y-axis inverted) is nearly perfectly correlated (r = -0.99) with the Gyre Index (**b**, black). The opposing sign of this relationship is irrelevant because the sign convention in EOF analysis is arbitrary. The second mode of North Atlantic SSH (**c**,**d**) has a tri-pole spatial pattern and its time series is correlated to the winter NAO (**d**, blue, r = 0.78).

Detrended

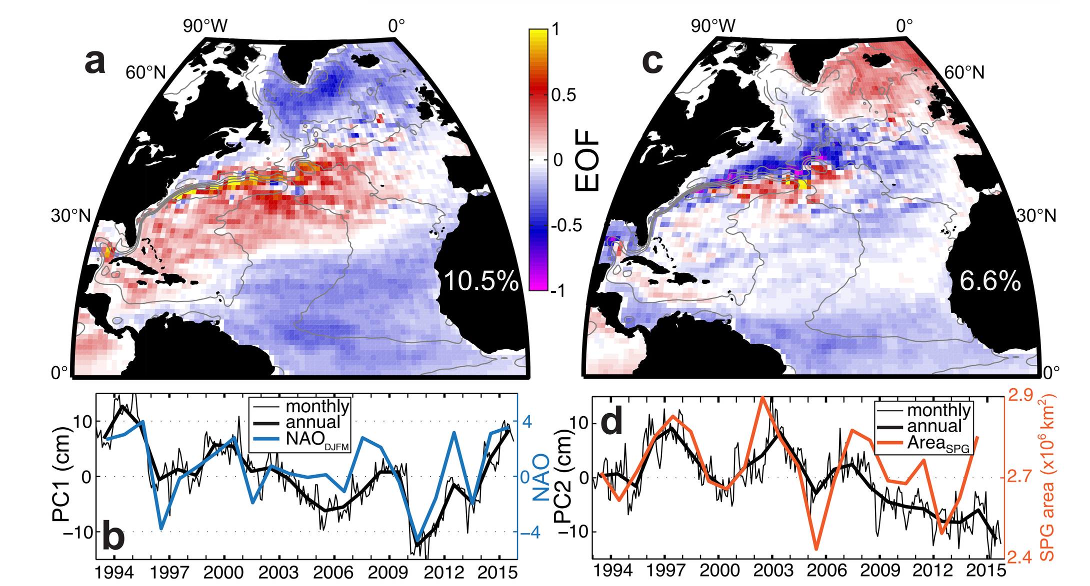

Figure 4. After detrending by the basin-averaged time series, the leading mode of North Atlantic SSH is the NAO mode (**a**,**b**). The second mode here weights negatively in the inter-gyre region and is correlated to the SPG area time series (r = 0.63) we derive in section 3.3. In this EOF analysis, the data are also normalized to their local variances, which provides equal weighting to each location. Without the normalization, the modes remain the same but explain about half of the variance reported here.

Conclusion 1: The Gyre Index primarily captures the basin-wide sea level rise in the North Atlantic. When the basin-averaged sea level rise signal is removed from the SSH data, the NAO is the dominant mode of variability.

3.3 A new metric of SPG size and strength from satellite altimetry

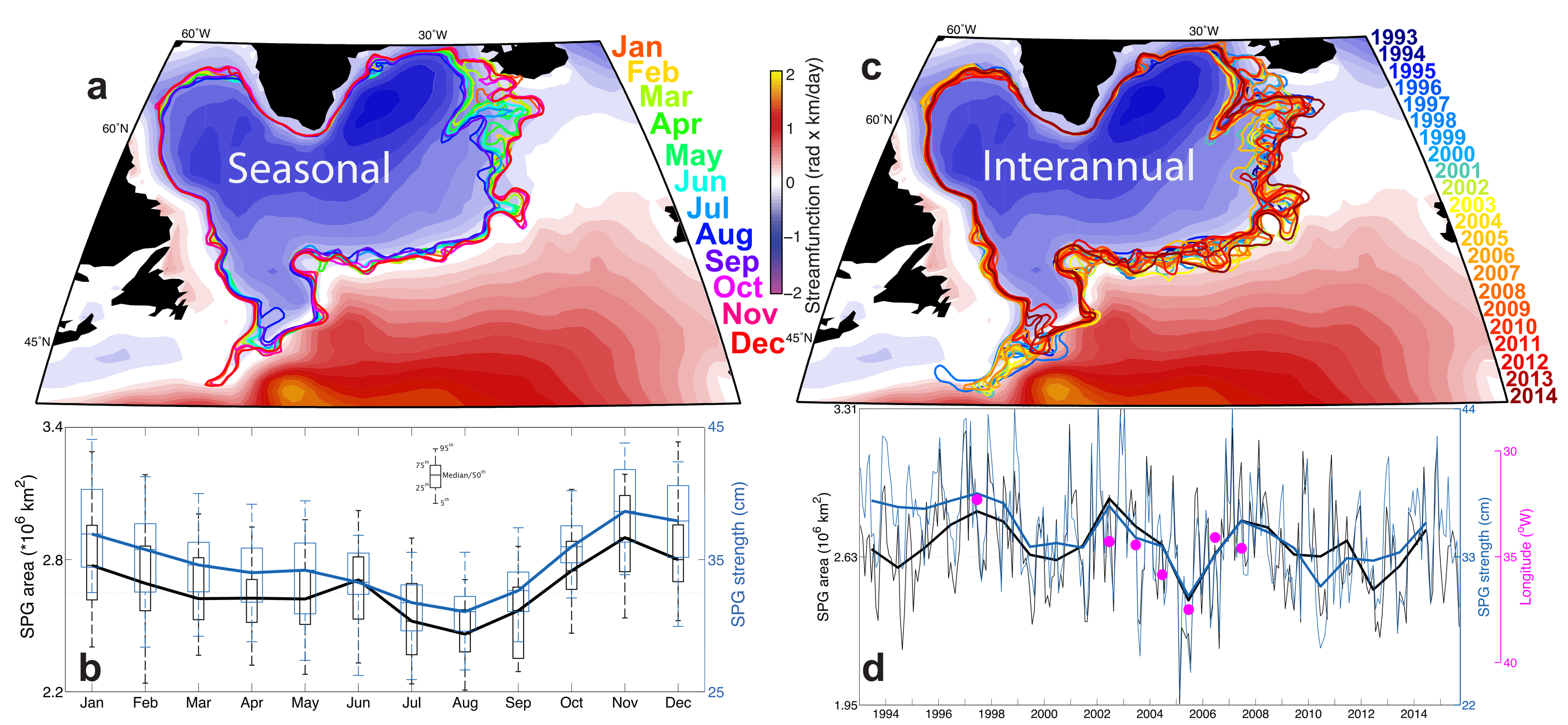

Figure 5. Seasonal (**a**,**b**) and interannual (**c**,**d**) variability in the SPG size and strength. Maps of the gyre boundary in panels a and c show little variability in the gyre's eastward extent and no coherent zonal shifts. Seasonally (**a**,**b**), the gyre is largest/strongest in the winter and smallest/weakest in the summer months. On interannual time scales (**c**,**d**), roughly 5-year oscillations in the time series' for both the size and strength dominate, with a decline in the gyre strength evident (5% per decade). The SPG area does not have a significant trend. The background colors in panels a and c refer to the time-mean stream function calculated from surface drifter velocities.[8] The pink dots in panel d refer to the longitude of the subpolar front (SPF) calculated by repeat hydrographic sections at 60°N.[9] Though the SPG area is well-correlated (r=0.70) with the SPF, the property variability in the eastern SPG varies independently of the SPG area - an unsurprising result given how little the eastern SPG boundary changes on both seasonal (**a**) and interannual (**c**) time scales.

Conclusion 2: The SPG strength has declined by ~5% per decade but the SPG area does not have a long-term trend. Changes to the eastward extent of the gyre are generally small and are not correlated to properties in the eastern SPG.

3.4 Forcing mechanisms of SPG size and strength

EOF analysis of North Atlantic WSC to determine dominant modes of wind forcing

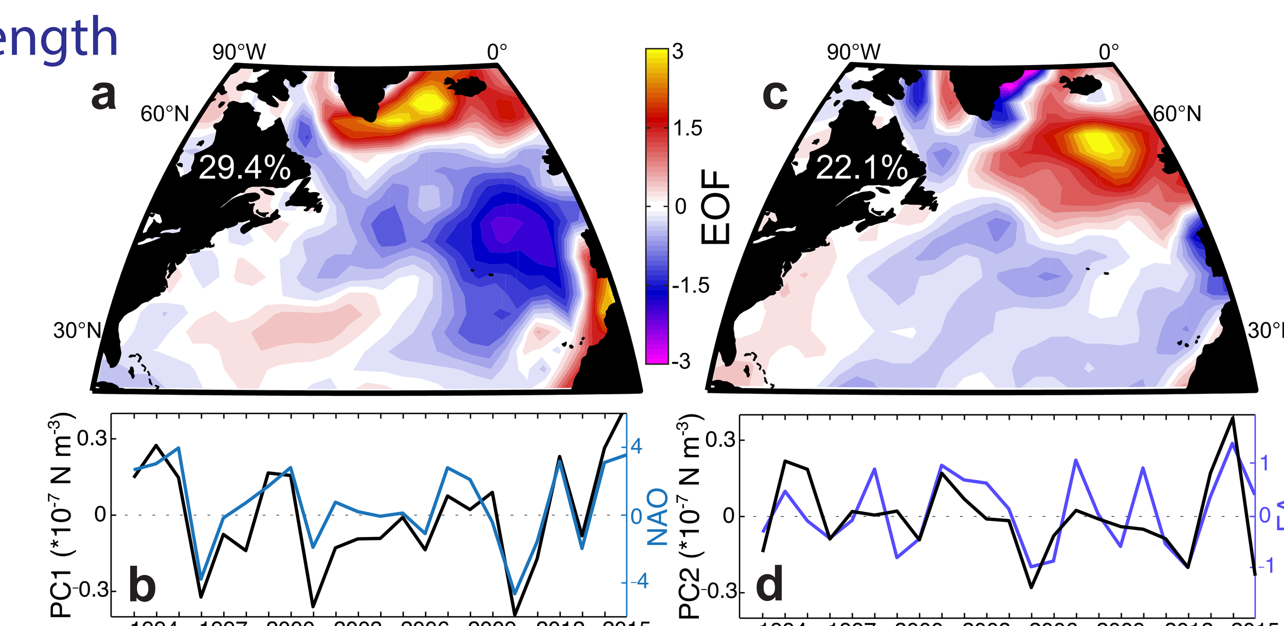

Figure 6. EOF1 of winter WSC (**a**) and its principal component (**b**) captures the NAO (r=0.89) with positive WSC over the Icelandic Low and negative WSC over the Azores High. The second mode (**c**,**d**) captures the EA pattern (r=0.61) which affects the latitude and orientation of the westerly winds over the North Atlantic. In the EA, the strong positive weighting over the eastern SPG indicates that when the EA is positive, the positive WSC over the Icelandic Low in the mean expands southward, and vice versa with the negative WSC over the Azores High expanding northward during negative EA years. Together, these modes capture >50% of the variance and the next mode explains ~8% of the variance.

3.4 Forcing mechanisms of SPG size and strength (cont.)

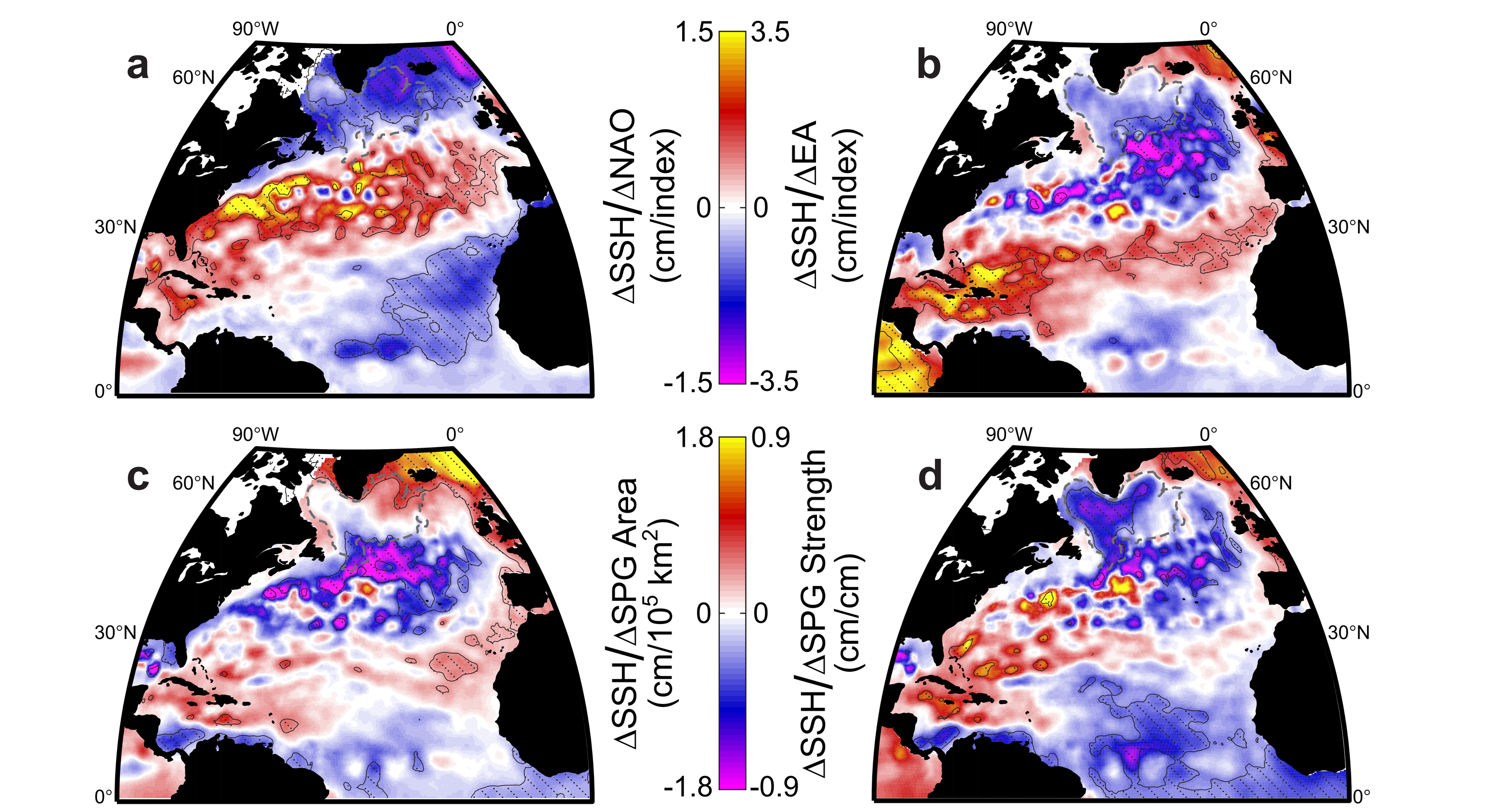

Figure 7. Linear responses of North Atlantic SSH to multiple time series: NAO (**a**), EA (**b**), SPG area (**c**), and SPG strength (**d**). The tri-pole pattern in (**a**) is similar to the EOF modes in section 3.2. The response to the EA (**b**) over the SPG resembles a combination of the response to SPG area (**c**) and SPG strength (**d**). When the EA is positive, the SSH over the SPG decreases, but moreso over the southern and eastern extents of the gyre. In contrast, when the NAO is positive, the SSH over the entire SPG declines (**a**), but does so nearly coherently over the entire gyre. Thus the difference between the gyre center and boundary (i.e. the gyre strength) is not affected by the NAO.

Conclusion 3: The East Atlantic Pattern (2nd EOF of winter WSC) impacts the size and strength of the SPG by lowering (raising) the SSH in the eastern SPG when the index is positive (negative).

4. Summary

- The Gyre Index does not isolate SPG dynamics from basin-wide sea level rise during the altimetry period (**Figs. 2, 3**). A basin-wide increase in SSH is not indicative of changes in ocean dynamics within the basin, thus the **Gyre Index should not be used to estimate variability in SPG circulation**.
- **A new metric of SPG circulation is derived from defining the gyre's boundary and center in satellite altimetry.** Variability in this index is consistent with in situ measurements of SPG circulation but not with the Gyre Index. The SPG area has no long-term trend and the SPG strength has declined slightly (5% per decade) over the 22 year study period (**Fig. 5**).
- **The size and strength of the SPG are not connected to property variability in the eastern SPG** (a metric of inter-gyre throughput) and we propose that this is due to the eastward extent of the SPG varying very little and not coherently across latitudes (**Fig. 5**).
- **The EA** weights heavily on the inter-gyre region (**Figs. 6c, 7b**) and **impacts the size and strength of the SPG by changing the orientation of the westerlies.** In contrast, though the NAO is a dominant mode of variability in North Atlantic SSH (**Fig. 6a,b**), it affects both the gyre boundary and center similarly (**Fig. 7a**), and thus the gyre strength does not respond to NAO forcing.

5. References

1. Häkkinen, S. & Rhines, P. (2004). Science, 304, 555-559.
2. Häkkinen, S. et al. (2011). JGR, 116, C03006.
3. Hátún, H. et al. (2005). Science, 309, 1841-1844.
4. Fischer, J. et al. (2010). GRL,37, L24610.
5. Daniault, N. et al. (2011).GRL, L07601.
6. Palter, J. et al. (2016). GRL, 42.
7. Cazanave, A. & Llovel, W. (2010). Ann. Rev. Mar. Sci., 2:145-173.
8. Rypina, I. et al. (2011). JPO, 41, 911-925.
9. Sarafanov, A. et al. (2008). JGR, 113, C12022.