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COMMENTARY
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Key Points:
- The dynamics represented by the "gyre index" has now segregated into the two leading EOF modes of SSH variability in the North Atlantic
- Although the concept of one single gyre index is strictly not meaningful anymore, most of its heritage is now carried by the new second PC
- By rigidly associating the first PC with the "gyre index", recent publications have presented unjustified criticism on a broad literature

Correspondence to:
H. Hátún,
hjalmarh@hav.fo

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On the Recent Ambiguity of the North Atlantic Subpolar Gyre Index

H. Hátún[1] **and L. Chafik**[2]

[1]Faroe Marine Research Institute, Tórshavn, Faroe Islands, [2]Geophysical Institute, University of Bergen, Bergen, Norway

Abstract The so-called gyre index appears to be related to core aspects of the North Atlantic subpolar gyre, meridional overturning circulation, hydrographic properties in the Atlantic inflows toward the Arctic, and in marine ecosystems in the northeast Atlantic Ocean. Recent publications, however, present a more linear version of this index with less of the key interannual-to-decadal variability. This has introduced uncertainty about the meaning and usefulness of the gyre index. We claim that these concerns are primarily caused by the fact that the recently produced "gyre index" is not the same as the original gyre index and discuss possible reasons.

1. Introduction

Variability in key physical and ecological aspects of the North Atlantic Ocean has typically been linked to the sea level pressure-based North Atlantic Oscillation (NAO) (Drinkwater et al., 2003) and the sea surface temperature-based Atlantic Multidecadal Oscillation (AMO) (Nye et al., 2014). Since many links to the NAO index broke after a major dip in the index during the winter of 1995–1996 (Drinkwater et al., 2013; Hátún et al., 2007), many researchers have turned their attention to the so-called gyre index (Häkkinen et al., 2011; Häkkinen & Rhines, 2004; Hátún et al., 2005). The gyre index is typically represented by the first principal component obtained through an empirical orthogonal function (EOF) analysis (Hannachi et al., 2007) of the sea surface height (SSH) field over the North Atlantic subpolar and subtropical gyres. The general aim of EOF analysis is to efficiently extract the most dominant modes of variability from large data sets by decomposing the associated space-time field into spatial patterns and time indices, or principal components (Wilks, 2006). This analysis has been demonstrated to be skillful in capturing the essential dynamics of the subpolar gyre (SPG), which is now recognized to have significant implications for a wide range of climatic (Lohmann et al., 2009a), and ecological (Hátún, Payne, Beaugrand, et al., 2009; Hátún, Payne, & Jacobsen, 2009; Hátún et al., 2016; Hátún, Azetsu-Scott, et al., 2017; Hátún, Olsen, et al., 2017; Hovland et al., 2013; Solmundsson et al., 2010) aspects of the North Atlantic Ocean.

We have recently become aware that there is some ambiguity in the interpretation of this gyre index in the literature and clarification is thus needed. Our investigation reveals that this confusion likely originates from the utilization of different satellite altimetry products, from the inclusion of different time periods and domains of the North Atlantic Ocean in publicized analyses. These studies have consequently led to different characteristics of the gyre index and therefore contradictory interpretations of the gyre-associated dynamics (Berx & Payne, 2017; Foukal & Lozier, 2017; Hátún, Olsen, et al., 2017). For example, some researchers have tied the index to the rotation intensity of the SPG (Foukal & Lozier, 2017; Lohmann et al., 2009b), while others focus on the size or the shape of the SPG (Hátún et al., 2016).

The first analyses of this kind, based on both altimetry (Häkkinen & Rhines, 2004) and model simulations (Hátún et al., 2005), provided a gyre index characterized by both decadal and subdecadal variability, and with a spatial imprint over the SPG and along the Gulf Stream. Häkkinen and Rhines (2004) used the 1° resolution of the NASA Pathfinder altimetry data set between 20°N and 65°N, and Larsen et al. (2012) produced a similar gyre index from the 1/3° Mercator grid altimetry data from AVISO (40°N–65°N). A subsequent analysis that included data from 0°N to 65°N obtained an index (1992–2012) more dominated by a long-term trend, where the subdecadal component, likely reflecting the highly variable winter convection in the Labrador and Irminger Sea, was less evident (Häkkinen et al., 2013).

In 2014, AVISO released a new version of Ssalto/DUACS altimetry products—the so-called *DUACS DT2014* (Pujol et al., 2016; available through http://marine.copernicus.eu/). These data include an extended

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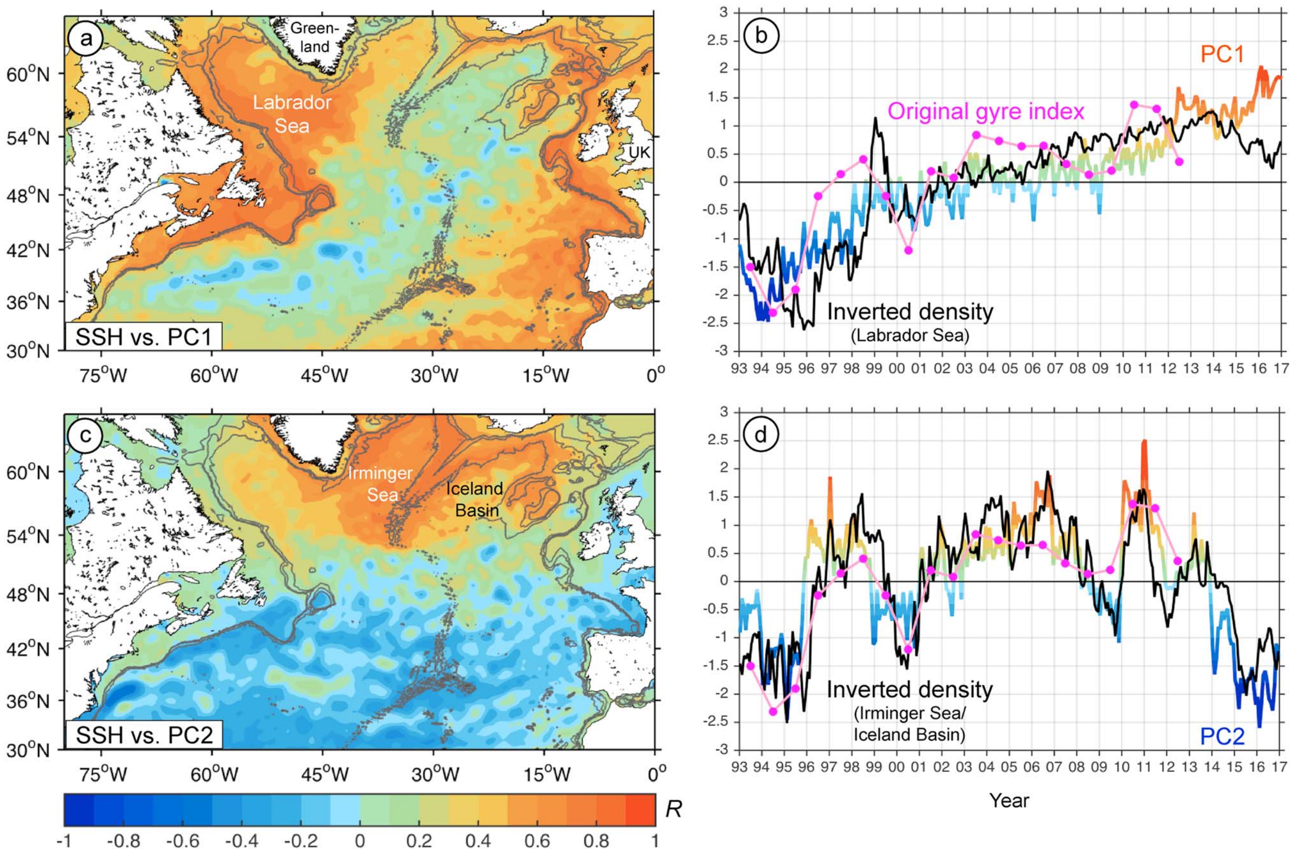

Figure 1. The two leading EOF modes derived from the *DUACS 2014* altimetry data set (1993–2016). (a) Correlations between PC1 and the SSH field; (b) PC1 (colored), the inverted deep Labrador Sea density anomaly (σ_2 averaged over the 1000–2500-m layer in the Labrador Sea; black); (c) correlations between PC2 and the SSH field; and (d) PC2 (colored) and the inverted density anomaly (σ_1 averaged over the top 1000-m layer in the vicinity of the Reykjanes ridge; black). The original gyre index (from Larsen et al. (2012), annual averages, pink) is added to (b) and (d). None of the time series are to scale. For the domain included, EOF1 and EOF2 explain 18.5 and 7%, respectively, of the total variance. An analysis based on a re-mapped coarser resolution (1° latitude × 1° longitude) SSH data set gave a very similar result.

reference period (1993–2012 instead of 1993–1999), a Cartesian 1/4° grid instead of the previous 1/3° Mercator grid, and higher spatial resolution south of 41.5°N and lower resolution north of this latitude. These changes have had a strong impact on the scientific content in these data (see https://www.aviso.altimetry.fr/en/data/product-information; Pujol et al., 2016), and the outcome from the EOF analysis has likewise changed, for example, less *weight* on the subpolar regions and more on the subtropical regions.

We illustrate these changes by re-applying the EOF analysis to the DUACS DT2014 altimetry data (Pujol et al., 2016)—monthly data for the region north of 30°N (cf. Figure 1). The first mode is comparable to the one recently published by Berx and Payne (2017). It consists of a principal component (PC1) that has less subdecadal variability than the original gyre index (Figure 1b) and, more importantly, a spatial pattern that is less distinctly associated with the shape of the SPG—especially with weaker loadings in the eastern SPG region (Figure 1a). This time series compares well with the density of Labrador Sea water estimated by averaging σ_2 (potential density referenced to 2000-db pressure level), obtained from the EN4 hydrographic data collection (Good et al., 2013) over the Labrador Sea and over the 1000- to 2500-m depth layer (Figure 1b). It is therefore clear that the first mode is associated with an integrated signal in the dense mode waters, and thus deepwater formation in the western SPG. In addition, it reflects the steady sea level rise as a consequence of anthropogenic warming observed during the satellite altimetry period (Church et al., 2013), as emphasized by Foukal and Lozier (2017).

Thus, the gyre index depends on the altimetry data source, the chosen spatial domain, and whether any normalization has been applied. Recent studies have spatially limited the analysis to the SPG domain, but despite this spatial focus, the first principal components based on the new *DUACS DT2014* (Berx & Payne, 2017; Hátún, Olsen, et al., 2017) are still more dominated by a long-term linear trend than is evident in the previous index presented by, for example, Larsen et al. (2012). We also note that the number of years included in the EOF analysis influences the PCs (not shown)—for example, an analysis based on the shorter 1993–2004 period results in a PC1 with a steeper post-1995 trend than apparent in Figure 1b.

In the most recent analysis of this kind, Foukal and Lozier (2017) also use the *DUACS DT2014* data set; however, they included most of the North Atlantic Ocean (0–70°N). Since their analysis involved a domain far beyond the SPG region, the spatial pattern associated with their first mode is similar to, but more homogenous than, the pattern in Figure 1a. It is therefore remarkably different from the patterns presented by Häkkinen and Rhines (2004) and Hátún et al. (2005).

The PC1 presented by Foukal and Lozier (2017, their Figure 2b), resembles Figure 1b, and thus exhibits a more linear trend than any of the previously published gyre index versions (Berx & Payne, 2017; Häkkinen et al., 2013; Häkkinen & Rhines, 2004; Hátún et al., 2005; Hátún, Azetsu-Scott, et al., 2017; Hátún, Olsen, et al., 2017; Larsen et al., 2012). A comparison of some of the previous gyre index versions is provided by Berx and Payne (2017, their Figure 7). Interpreting their rather unidirectional PC1 trend as the “gyre index”, Foukal and Lozier (2017) express the following concerns about the usefulness of the gyre index: (i) the SSH variability across the entire North Atlantic—not just the SPG—determines the gyre index, which thus mostly reflects a basin-wide sea level rise during the study period; (ii) the NAO is not a dominant control on the size and strength of the SPG; and (iii) the weighting of the leading SSH mode is weak in the eastern SPG, and the gyre index can therefore not explain variability in the Rockall region, as previously suggested (e.g., Hátún et al., 2005; Larsen et al., 2012).

A principal reason for the present confusion in the literature is that the new publications (Berx & Payne, 2017; Foukal & Lozier, 2017; Hátún, Olsen, et al., 2017) rigidly treat PC1 as the gyre index. Many of the concerns expressed by Foukal and Lozier (2017) are rooted in this mistake.

With merely a linear trend represented by the first mode, much of the dynamic variability in the SPG has now shifted to the second mode. The second mode primarily reflects sea surface height variability in the Irminger Sea-Reykjanes Ridge-Iceland Basin region (Figure 1c), and is characterized by both decadal-scale variability and marked *dips* in 1994–1995, 1999–2000, 2008–2009, 2012, and 2014–2015 (Figure 1d). All these marked depressions are clearly reflecting years with increased deepwater formation in the northern North Atlantic (de Jong & de Steur, 2016; Yashayaev & Loder, 2016), and therefore a denser water column and lower sea surface heights there through the steric effect (Gill, 1982). The second mode is thus very sensitive to convection events in the Irminger Sea, and closely reflects the density of the lighter mode waters adjacent to the Reykjanes Ridge (Figure 1d) estimated by averaging σ_1 over the upper 1000 m. As previously noted, this mode is also linked to NAO-like atmospheric forcing (Esselborn & Eden, 2001; Foukal & Lozier, 2017, their Figure 2). However, the second principal component (PC2) is probably a better proxy for the marine climate in the subpolar Atlantic than the NAO index is, since it integrates the oceanic imprint of the real atmospheric forcing—wind stress curl and air-sea heat exchanges—which, in turn, are often proxied by the NAO. The recent resurrection of deepwater formation in the Labrador-Irminger Seas after 2013 (de Jong & de Steur, 2016; Yashayaev & Loder, 2016) is, using the new altimetry data, not captured by PC1, and the imprint of this marked inflation of the SPG is therefore now represented by PC2.

The here presented PC1 and PC2 are positively correlated from 1993 to the late 2000s (R = 0.61, 1993–2008), which explains why these two leading modes initially became merged into one *gyre mode*, represented by the gyre index, in the previous publications (Häkkinen & Rhines, 2004; Hátún et al., 2005). A shift, however, occurred around 2009 after which the trend and inter-annual variability in PC1 and PC2 became anticorrelated (cf. Figures 1b and 1d). This recent fact, and the usage of the altered DUACS DT2014 altimetry data, explains why the gyre-related dynamics now become segregated into the two leading EOF modes. Unraveling the relative impact from using the different data sources versus including the extended post-2010 period, respectively, requires an in-depth analysis of the altimetry data, which is beyond the scope of the present commentary.

Since the two leading PCs are uncorrelated over the entire 1993–2017 period and represent variability in different geographical locations (Figures 1a and 1c), we find it unlikely that both the trend and the convection-related pulses, hereafter, can be captured by a single indicator time series in a statistically rigorous way. That is, the concept of one single gyre index does strictly not hold anymore. However, we have been able to reconstruct (Figure 2) the original gyre index based on PC1 and PC2 through multiple linear regression (Wilks,

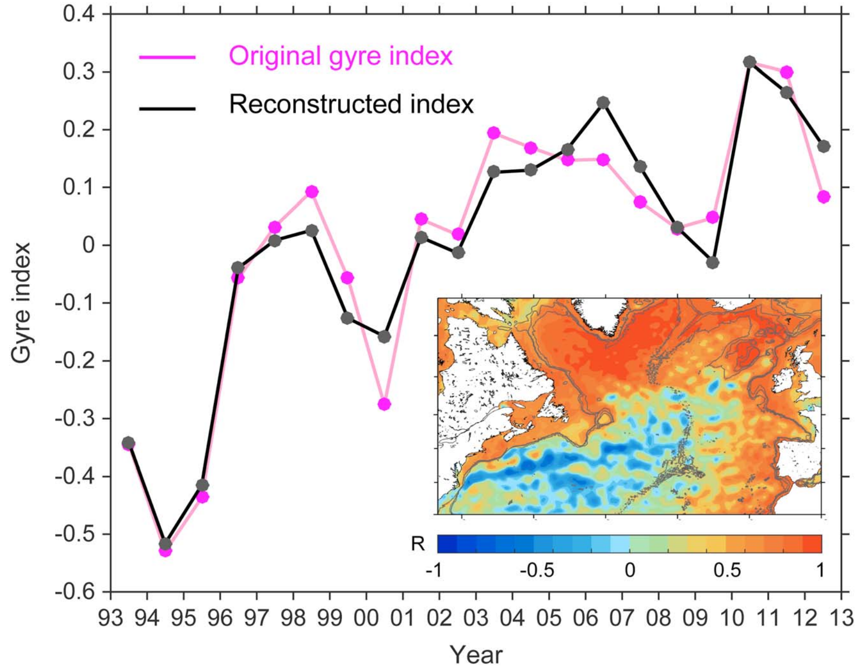

Figure 2. The original gyre index (pink), produced by Larsen et al. (2012) using the DT 2010 data, compared to the reconstructed index (black), based on both PC1 (Figure 1b) and PC2 (Figure 1d). Annual averages (January–December) are presented. The inset shows the correlation map between the reconstructed index and the SSH field over the North Atlantic.

2006). This reconstructed index is closely correlated with the original gyre index (R = 0.97), indicating that these proxy records collectively capture the main mode water changes in the subpolar North Atlantic and along the Gulf Stream (Figure 2, inset).

It might be an advantage, or clarification, that the EOF analysis now segregates the trend-like and the characteristic inter-annual variability into two separate modes. PC1 represents the gradual changes in the deep dense mode waters in the Labrador Sea, and the western side of the Irminger Sea, as well as near the continental margins, which are only moderately *disturbed* by the oceanic variability. PC2 is intimately linked to marine climate in the highly energetic, changeable, and biologically productive waters between Greenland and the Rockall Plateau, and to the Gulf Stream/subtropical gyre region (Figures 1b and 1d). Our recommendation to the oceanographic community is to carefully use PC1 and/or PC2 depending on the region of interest and research question. If any, it would be more correct to use either PC2 (Figure 1d) or the reconstructed index based on both PC1 and PC2 (Figure 2), as a new gyre index, rather than PC1 alone as done by Foukal and Lozier (2017) and Berx and Payne (2017).

We agree with Foukal and Lozier (2017) that a more direct measure of the SPG size and strength is desirable, but the approach used by these authors is not appropriate. The marine climate in the northeast Atlantic is highly sensitive to whether the SPG encompasses the Rockall Plateau or not, and this state of inclusion shifts between the years (Hátún et al., 2005; Hátún, Payne, & Jacobsen, 2009). Foukal and Lozier (2017) discuss the size of the SPG, which they define as the largest closed contour of each monthly SSH field. Since not all eastern subpolar water fall within this definition, which seems to be strongly bathymetrically constrained, their analysis ignores parts of the essential dynamics beforehand.

The presented altimetry analysis is, in itself, not novel. It is merely used to show that the criticism by Foukal and Lozier (2017) of the literature which has utilized the gyre index is rooted in their simple association between PC1 and the gyre index. We do not provide an in-depth analysis of the updated altimetry data set (DT2014), and the search for a suitable direct metric for the SPG shape/dynamics, based on more in-depth analysis, therefore remains warranted.

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