The impact of Labrador Sea temperature and salinity variability on density and the subpolar AMOC in a decadal prediction system

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Abstract Labrador Sea density variability is important for Atlantic Meridional Overturning Circulation (AMOC) dynamics and hence decadal variability in the Atlantic. We investigate whether temperature or salinity dominate top 500 m interannual Labrador Sea density variability in gridded observations, an assimilation of the observations, and a set of multiannual hindcasts. We find that salinity dominates in the observations and assimilation. In the hindcasts salinity remains dominant for the first year but from year three these revert to the same temperature dominance seen in the underlying climate model. This is due to damping of the interannual salinity variability, possibly caused by unrealistically large convection that develops. Crucially, the hindcasts have high correlation skill in temperature/salinity throughout, but no skill in density, dynamic sea level, or the subpolar AMOC due to the incorrect drivers. This highlights the importance of correctly simulating both the sign and magnitude of temperature/salinity variability in a prediction system.

1. Introduction

The climate is changing at an unprecedented rate [Bindoff et al., 2013] due largely to greenhouse gas (GHG) concentrations that are now higher than at any point in almost one million years [Hartmann et al., 2013]. Nonetheless, despite globally well mixed GHGs, the pattern of both projected long-term and predicted short-term (over several years) climate change is not homogeneous [Kirtman et al., 2013; Collins et al., 2013]. In and around the North Atlantic this is particularly apparent, with recent cooling in the North Atlantic subpolar gyre (NASPG) [Drijfhout et al., 2012] but accelerating warming and sea ice loss in the Arctic [Stroeve et al., 2014]. Improving our understanding of the drivers of these changes, on both multiyear prediction timescales and multidecadal projection timescales, is crucial for effective planning of adaptation and mitigation strategies [Hodson et al., 2014].

The NASPG has been shown to be an important region for the initialization of multiannual/decadal forecasts [Dunstone et al., 2011]. The NASPG is also often an active region in mechanisms of decadal or longer-term variability diagnosed in free-running climate models [Frankcombe et al., 2010; Liu, 2012; Menary et al., 2012]. The northern lobe of the Atlantic Multidecadal Oscillation (AMO) [Delworth and Mann, 2000; Roberts et al., 2013] exists within the NASPG and has been linked to decadal variability in Atlantic hurricanes [Goldenberg et al., 2001], Sahel droughts [Folland et al., 1986], and summertime European climate [Sutton and Hodson, 2005]. Recent observational analyses suggest a role for ocean dynamics in determining the variability of the AMO on these long timescales [McCarthy et al., 2015].

Within the NASPG, differing representations of key balances within the Labrador Sea region (such as whether interannual variability in near-surface temperature or salinity drives interannual density variability) may go some way to explaining the wide range of potential physical mechanisms of annual to decadal variability found in climate models [Menary et al., 2015a] as well as the particular location of biological activity [Carmack, 2007]. We focus on the near surface (top 500 m) as this represents the link between the atmosphere and slowly varying deep ocean and because decadal variability in the NASPG/Labrador Sea—coherent over the top 500 m—has been previously shown in a similar version of the model in this study [Menary et al., 2015b]. In that work, it was found that Labrador Sea convection acted to spread the top 500 m signal to even greater depths, thus providing a route for near-surface variability to influence the deep ocean. In addition, steric sea level changes associated with Labrador Sea density variability have impacts both locally as well as further...
afield via their effect on the baroclinic circulation in the rest of the NASPG. Variability in the Labrador Sea is intimately linked to the Atlantic Meridional Overturning Circulation (AMOC), for which Labrador Sea water contributes to the southward flowing limb [van Sebille et al., 2011]. Further, deep (1200–3000 m) horizontal density gradients between the Labrador Sea and eastern NASPG have been shown to be related to the strength of the AMOC in prediction systems [Hermanson et al., 2014].

It is not clear how representative the modes of variability in climate model control simulations (i.e., without imposing time-varying historical estimates of external forcings) are of the present-day climate that is undergoing transient climate change. Similarly, it is unclear whether the preference for one mode or another in a particular model represents a fundamental feature of the climate model, or whether the introduction of real-world variability could shift the model to a more observationally consistent mode — as has been shown for situations in which salinity flux correction is applied [Park et al., 2016]. Specifically, for a model with temperature-dominated near-surface interannual density variability in the Labrador Sea, does assimilation of the real-world ocean state (which shows signs of salinity-dominated near-surface interannual density variability, see section 3.1), improve the manifestation of ocean variability both locally and beyond?

To explore these issues, we investigate the dominant components of Labrador Sea near-surface (top 500 m) interannual density variability in observation and model-based estimates of the real world. Our three key research questions are as follows:

1. Which of temperature or salinity dominates interannual density changes in the Labrador Sea over the period 1960–2013 in observations?
2. For a climate model with an apparently incorrect dominant component of density variability, does assimilation of the observed ocean state into a prediction system alter this in subsequent forecasts?
3. To what extent does simulating the correct dominant component of density variability in forecasts affect the skill of the model at simulating the ocean state in this region and large-scale circulation in the wider North Atlantic?

2. Data and Methods

We use optimally interpolated ocean observations of temperature and salinity from the “EN4” data set [Good et al., 2013], an updated version of “EN3” [Ingleby and Huddleston, 2007] that was previously used in, for example, estimates of global ocean heat content [Domingues et al., 2008]. The data are gridded on to a 1 × 1° grid and infilled using fixed decorrelation length scales (except near the equator). EN4 spans the period 1900 to present day (with approximately a 2 month lag), but for direct comparison with the prediction system (discussed next) we use the period 1960–2013 inclusive. EN4 provides spatially and temporally complete data required to initialize dynamical models, but we note that the globally consistent methods of data infilling may yield different estimates to more bespoke methods [Yashayaev and Loder, 2016]. To what extent EN4 is an objective “truth” is not the subject of this study, but regardless, it does represent the truth from which the prediction system is initialized and subsequently aims to predict.

The Met Office Decadal Prediction System 3 (DePreSys3) [Dunstone et al., 2016] combines the global ocean analysis of Smith and Murphy [2007] with the climate model HadGEM3-GC2 (hereafter GC2) [Williams et al., 2014]. GC2 is a fully coupled climate model, incorporating the NEMO ocean [Madec, 2008] at version 3.4 (with 75 vertical levels and a horizontal resolution of 0.25°) and the Unified Model Global Atmosphere 6.0 (GA6.0 [Williams et al., 2014], with 85 vertical levels and a horizontal resolution of N216, equivalent to 92 km at the equator). Winds and temperatures from ERA-40 [Uppala et al., 2005] are relaxed (assimilated) into the atmosphere with a 6 hour timescale that tapers off toward the ocean interface. The Smith and Murphy [2007] analysis is relaxed into the ocean with relaxation timescales of 10 days for temperature and salinity and 1 day for ice extent over the period 1960–2013. Full fields are used for the ocean relaxation, as opposed to the anomaly method previously used [Smith et al., 2007], the result of which is hereafter referred to as “the assimilation.” Although the ocean analysis to which the assimilation is relaxed uses the same profile data as in EN4, this information is further spread in the analysis using global covariances (inherently including dynamics and teleconnections), which can result in different state estimates, particularly in poorly observed regions. Additionally, cross covariances in temperature and salinity are used; i.e., information from the temperature field can be used to fill in gaps in the salinity field and vice versa.
Figure 1. Time series (top) of volume-averaged density ($\rho_{500}$, black, referenced to the surface) over the top 500 m of the Labrador Sea (45–65°W, 55–65°N, as depicted in Figure 3) in EN4 (solid) and the DePreSys3 assimilation (dash dotted). Also shown are density variations due to temperature changes ($\rho_T_{500}$, blue) and density variations due to salinity changes ($\rho_S_{500}$, red). Vertical bars (green) denote the year of initialization of the 21 DePreSys3 hindcasts. Also shown (bottom, grey) are the annual total number of salinity observations that are binned into the 407–491 m layer in the Labrador Sea in EN4 (the deepest layer included in our volume).

Subsequently, hindcast simulations are performed, using the assimilation as the initial conditions and allowing the coupled system to evolve freely. These are initialized on 1st November every 2 or 3 years from 1960 to 2012 (see Figure 1, vertical green lines). Hindcast data where there is no parallel assimilation (e.g., after 2013) are ignored in our analysis. Each hindcast is formed of 10 ensemble members separated by providing different seeds for the stochastic physics scheme. For simplicity in the subsequent analysis we examine annual means that are from January to December inclusive.

3. Results

3.1. Observed Interannual Density Variability in the Labrador Sea

To estimate the dominant component of near-surface interannual density variability in the Labrador Sea, we compute the annual mean volume-averaged density ($\rho_{500}$) in the region 45–65°W, 55–65°N, top 500 m, hereafter referred to as the Labrador Sea (Figure 1). Observations in the Labrador Sea, particularly of salinity, are relatively sparse prior to the 1990s (Figure 1, bottom) [Menary, 2015, their Figure 3.1], which may contribute to the apparent sudden peak in density in 1962 in EN4. Indeed, comparison against the densities computed over the same volume in the assimilation suggests a much smaller density anomaly at this time (Figure 1).

The early 1960s notwithstanding, there is generally good agreement between the optimally interpolated observations (a statistical model) and the assimilation (a dynamical model). The annual correlation between Labrador Sea density estimated in EN4 and the assimilation is $r = 0.56$, though this increases to $r = 0.72$ if just the second halves of the time series are used. That is, there is better agreement when both estimates are constrained by an increasing number of actual observations. We also note that there is less apparent density variability since Argo observations [Riser et al., 2016] began to be ingested into the observations database in the early 2000s. This leads us to question whether large peaks in near-surface density prior to the early 2000s are to some extent a sampling issue.

In order to estimate the dominant component of interannual density variability in EN4 and the assimilation, we compute the components of density due separately to temperature and to salinity. This is achieved by, for example, using the time-averaged salinity in the seawater equation of state to give the density changes due to interannual temperature variability (for the given salinity mean state), $\rho_T_{500}$ [Delworth et al., 1993]. A similar calculation using time-averaged temperature and annually varying salinity gives $\rho_S_{500}$. We calculate $\rho_{500}$,
\(\rho_{500}\) and \(\rho_{500}\) for each grid point before volume averaging over the Labrador Sea top 500 m, but note that our results are not sensitive to instead first volume averaging temperature/salinity before computing the densities. Additionally, we linearize using annual data but note that linearizing about a seasonal climatology and subsequently constructing annual means changes the resulting correlations by less than 0.02. To test whether linearizing density into components due to temperature and salinity (by using constant time-mean salinity or temperature) is a good approximation, we estimate the density due to the sum of \(\rho_{500}\) and \(\rho_{500}\). For the period 1960–2014, this sum explains \(>99\%\) of the interannual variance in \(\rho_{500}\) in EN4 as well as \(>99\%\) of the interannual variance in \(\rho_{500}\) in the assimilation—such as such the linearization can be considered acceptable.

As with the actual density (\(\rho_{500}\)), the density due to either temperature variability (\(\rho_{500}\)) or salinity variability (\(\rho_{500}\)) agrees well between EN4 and the assimilation. The correlation between EN4 and the assimilation for \(\rho_{500}\) is \(r = 0.98\), and for \(\rho_{500}\) is \(r = 0.90\). Breaking density variability down into its components also reveals that the peak in density in 1962 is due to a large positive salinity anomaly in EN4 but that this salinity anomaly is apparently absent in the assimilation (Figure 1).

Finally, we use \(\rho_{500}\) and \(\rho_{500}\), along with the actual density (\(\rho_{500}\)), to estimate the dominant component of interannual density variability. The correlation between \(\rho_{500}\) and \(\rho_{500}\) in EN4 is \(r = 0.67\) and in the assimilation is \(r = 0.74\). Similarly, the correlation between \(\rho_{500}\) and \(\rho_{500}\) in EN4 is \(r = -0.13\) and in the assimilation is \(r = -0.41\). As such, it can be seen that interannual salinity variability in the near-surface Labrador Sea is responsible for the interannual density variability in this region and that temperature-induced density variability acts to oppose these salinity-dominated changes. As noted above, we have focused on top 500 m depth averages, but the dominance of salinity in driving interannual Labrador Sea density variability extends down to 1 km in the assimilation, below which temperature effects become more important (supporting information Figure S1a). However, from Figure 1 it can also be seen that the trend (not interannual variability) to lighter waters since 1995 is likely due to temperature (i.e., warming), as noted elsewhere [Kieke and Yashayaev, 2015]. Subsampling to the central Labrador Sea to remove the possible counter effects of boundary currents, after Yashayaev and Loder [2016], provides very similar results (supporting information Figure S2).

Subsampling to the central Labrador Sea to remove the possible counter effects of boundary currents, after Yashayaev and Loder [2016], provides very similar results (supporting information Figure S2). Separately, it is worth clarifying that wintertime convection is driven by intraseasonal surface temperature (density) variability but that its efficacy is modulated by interannual variability in the background density profile, which shows an important role for salinity [Lilly et al., 1999]. It is this background profile that is the focus of this study.

### 3.2. Interannual Density Variability in the Labrador Sea in Multiyear Hindcasts

Both GC2 and a longer simulation using a similar precursor model have been shown to have temperature-dominated interannual density variability in the near-surface Labrador Sea [Menary et al., 2015a]. This has been linked to their mean state biases in which both models are too warm and salty in the Labrador Sea. In this regime, due to the nonlinear equation of state, a given temperature change is more able (and a given salinity change less able) to change the density than if the models were cooler and fresher. It is also worth noting that anomalies in near-surface temperature and salinity in this region generally covary \((r = 0.82\) in EN4 and \(r = 0.92\) in the assimilation for the Labrador Sea). Given this, whether the system responds more strongly to temperature or salinity has potentially significant implications for forecasts of density and related variables.

This motivates our second question: For a climate model (GC2) where interannual density variability is apparently incorrectly dominated by temperature (i.e., \(\rho_{500}\)), does assimilation of the observed ocean state into a prediction system (DePreSys3, based on GC2) alter this in subsequent forecasts? To investigate whether the hindcasts maintain the correct dominant component of interannual density variability, we show the correlation in the hindcasts between \(\rho_{500}\) and \(\rho_{500}\) as well as the correlation between \(\rho_{500}\) and \(\rho_{500}\) (Figure 2a, solid). In addition, as each hindcast ensemble member is only 5 years long, and to control for the fact that the hindcasts are initialized throughout a time window that shows some multicadal variability (cf. Figure 1), we also estimate the anomalies in, for example, \(\rho_{500}\) as the difference between the present and previous year of the hindcast (Figure 2a, dashed). That is, the \(\rho_{500}\) anomaly at year 2 is the difference between \(\rho_{500}\) in all hindcasts from years 2 to 1. The first value, at a lead time of 1 year, is the difference between the anomalies in the hindcast and the previous year from the assimilation. In either case, we compute the full density anomaly (\(\rho_{500}\)) in the same way and then correlate the full densities with both \(\rho_{500}\) and \(\rho_{500}\) to explore which of \(\rho_{500}\) or \(\rho_{500}\) generally drives the \(\rho_{500}\) anomaly. This is repeated for each lead time. As such, each correlation includes 21 pairs of values, each of which is the mean over 10 ensemble members.
Figure 2. (a) Correlation (solid) between density ($\rho_{500}$), temperature-induced density ($\rho_{T,500}$, blue), and salinity-induced density ($\rho_{S,500}$, red) across all 21 DePreSys3 hindcasts as a function of lead time. Also shown are correlations (dashed) between year to year density changes and temperature-induced (blue) and salinity-induced (red) year to year density changes, for comparison with Figure 3 and as described in the text. Shown on the left are the mean correlation (cross) and standard deviation (whiskers) from the DePreSys3 assimilation run, with uncertainties estimated using a 20 year moving window. Additionally, on the right are the mean correlation and standard deviation of correlations (using a 20 year moving window) for the GC2 control simulation and the HadCM3 control simulation. (b) The correlation skill scores as a function of lead time in the DePreSys3 hindcast ensemble mean compared against the DePreSys3 assimilation for a selection of variables: Labrador Sea depth-averaged temperature ($T_{500}$, blue), salinity ($S_{500}$, red), and density ($\rho_{500}$, black) as well as dynamic sea level (DSL, dashed) over the same region and the AMOC at 45°N, 1000 m (orange).

Figure 2a shows that with increasing lead time the year to year Labrador Sea density variability in the hindcasts becomes more temperature-dominated (blue lines) and correspondingly less salinity-dominated (red lines). In terms of the models/systems involved, the hindcasts move from the assimilation system (DePreSys3) choice of interannual density control (salinity) to the base climate model (GC2) choice of interannual density control (temperature, Figure 2a, right-hand side). Somewhat surprisingly, the majority of this switch occurs within 2 years of initialization, possibly related to the rapid adjustment often seen with full-field assimilation and prediction [Smith et al., 2013]. The method of describing density components using year to year changes (dashed lines) also highlights that much of the change occurs within the first year. This switch from salinity-
temperature-dominated density variability is likely to have fundamental implications for the subsequent skill in near-surface density prediction in this region, which we investigate in section 3.4. However, first we investigate the cause of the switch with the hope of providing useful information for the improvement of decadal prediction systems.

3.3. The Switch to Temperature-Dominated Density Variability in Multiyear Hindcasts

In order to investigate the changing nature of density variability in the Labrador Sea in the DePreSys3 hindcasts, we compute the difference in magnitude of typical salinity-induced and temperature-induced density anomalies (Figure 3). We do this both for the assimilation (Figure 3, top left), using the mean and standard deviation in temperature and salinity to estimate typical $\rho_s$,$500$ and $\rho_T$,$500$ anomalies, as well as for the hindcasts (Figure 3, left column, see Text S1 in the supporting information for further details).

It can be seen that $\rho_s$,$500$ anomalies are typically larger than $\rho_T$,$500$ anomalies in the assimilation (Figure 3, top left, see supporting information Figures S3 and S4 for a breakdown into the individual components), and their importance can be seen in Figures 1 and 2a. In addition, the spatial maps reveal a gradient from temperature-dominated variability in the eastern Labrador Sea, to salinity-dominated variability in the western Labrador Sea. In the hindcasts, at lead times of 1 year (months 3–14), $\rho_s$,$500$ anomalies are now even more dominant compared to $\rho_T$,$500$ anomalies throughout the Labrador Sea. This is again consistent with the initial increase in salinity-dominated variability between the assimilation and the first year of the hindcasts seen in Figure 2a (either solid or dashed). At lead times of 2 years (15–26 months) there is an increasing role for $\rho_s$,$500$, and at lead times from 3 years onward $\rho_s$,$500$ is dominant (Figure 3, left column, last three rows). Note that repeating this analysis using just the more well observed second half of the period yields no substantive differences except a slight hastening of the switch from salinity-dominated to temperature-dominated variability at lead times between 2 and 3 years (not shown).

The inferred dominant component of density variability for a given region can change due to some combination of (1) changes in the mean state (i.e., moving into a regime in temperature/salinity space where a given temperature/salinity change has a weaker/stronger effect on the density [cf. Menary et al., 2015a]) or (2) changes in the magnitude of the temperature/salinity variability. To estimate the relative importance of these contributions, we let one of either (a) the mean state (Figure 3, middle column) or (b) the magnitude of temperature/salinity variability (Figure 3, right column) change with lead time in the hindcasts while maintaining the other (variability or mean state) at the assimilation values (see Text S1 in the supporting information for further details).

Considering first the middle column it is apparent that the change in temperature/salinity mean state in the hindcasts is not responsible for the shift from salinity-dominated to temperature-dominated density variability. Figure 3 (middle column) shows that if the hindcasts were able to maintain the same interannual variability in temperature and salinity as in the assimilation, then $\rho_s$,$500$ would remain dominant over $\rho_T$,$500$ (i.e., $\rho_s$,$500$ minus $\rho_T$,$500$ would remain positive throughout). However, the actual hindcasts show a transition from salinity-dominated to temperature-dominated density variability (Figure 3, left column). This test of the mean state effect shows that despite the rapid initial adjustment [Smith et al., 2013], there is not a large enough change in the mean state to sufficiently alter the characteristic dominant component of density variability. Indeed, we note that the hindcast-mean 0.1 K warming and 0.1 PSU salinification that occurs between the hindcasts is not responsible for the switch from salinity-dominated to temperature-dominated density variability (Figure 3, left column, last three rows).

Considering now the right column, it appears that the (changing) magnitude of interannual variability in temperature and salinity in the hindcasts is indeed the cause of the switch from salinity- to temperature-dominated density variability. Here we have combined the temperature/salinity mean state from the assimilation with the lead time-dependent variability from the hindcasts. In the first year, $\rho_s$,$500$ still dominates over $\rho_T$,$500$ but from the second year onward $\rho_s$,$500$ becomes less important (i.e., $\rho_s$,$500$ minus $\rho_T$,$500$ becomes negative). The magnitude of temperature-induced density anomalies at lead times longer than 2 years is generally larger than the magnitude of salinity-induced density anomalies at these lead times. Supporting information Figures S3 and S4 show that it is salinity (rather than temperature) variability that has changed the most in the hindcasts, becoming damped compared to the assimilation and thus having less of an impact on interannual density variability. Indeed, at a lead time of 5 years the standard deviation of annual mean Labrador Sea volume-averaged salinity across the hindcasts is 35% of the assimilation annual standard deviation, compared to 62% for temperature.
Figure 3. Spatial maps of the difference in characteristic magnitudes of \( \rho_{500} \) and \( \rho_T \) anomalies in the (top left) DePreSys3 assimilation and (left column) hindcasts, estimated by combining the mean state temperature and salinity with one standard deviation of the year to year changes in the same. Standard deviations in the hindcasts are across all 21 hindcasts and ensemble members. Also shown are the split into lead time-dependent (middle column) hindcast mean state effects and (right column) hindcast variability effects. See Text S1 in the supporting information for more details.
In the absence of an accurate, closed, real-world salinity budget for the Labrador Sea it is not possible to
diagnose which of the simulated salinity fluxes are incorrect and thus why the salinity variability is damped
(note that the salinity budget in the DePreSys3 assimilation is to an unknown extent the response of the
model to the applied temperature and salinity increments). Nonetheless, it is possible to calculate the loca-
tion in the Labrador Sea where the interannual salinity variability is most damped and to suggest possible
processes that could contribute to the damping. The central Labrador Sea, over approximately the top 500 m,
has the majority of the salinity damping (not shown), located over the region of deepest mixed layers. While
the DePreSys3 assimilation has a realistic March mixed layer depth, the hindcasts quickly develop unrealisti-
cally deep vertical mixing (supporting information Figure S5). It is possible that this excessive mixing could
damp the salinity more than the temperature as the mixed layer temperature is more strongly coupled to
atmospheric fluxes than the salinity. The vertical structure of advected anomalies may also play a role. Further
exploration is provided in the supporting information. In the next section we explore what impact the
switch from salinity-dominated to temperature-dominated density variability has on the skill of related ocean
variables in the Labrador Sea.

3.4. Impacts on Hindcast Skill in the Labrador Sea
The lead time-dependent correlation skill scores for annual mean top 500 m volume-averaged temperature
\(T_{500}\), salinity \(S_{500}\), and density \(\rho_{500}\) in the Labrador Sea, measured against the assimilation, are shown in
Figure 2b. The skill in \(T_{500}\) and \(S_{500}\) is high throughout the 5 years of the hindcasts though not significantly
different from persistence; i.e., the skill appears to arise from persistence. Although salinity variability in the
hindcasts is damped compared to the assimilation (supporting information Figure S3), it is apparent from the
high skill that salinity in the hindcasts is generally still varying in the correct direction (note that correlation
skill does not measure amplitude). However, despite the high correlation skill in temperature and salinity, the skill
in density in the same region is poor after the first year and eventually becomes strongly negative. Although
disappointing, this is also entirely consistent with a synthesis of our previous results, namely, (1) temperature
and salinity anomalies generally covary in this region \((r = 0.92)\), (2) temperature and salinity variability show
good skill (Figure 2b), and, crucially, (3) the dominant component of density variability switches from salinity
to temperature in the hindcasts (Figure 2a).

The result of temperature becoming the dominant component appears to be that the density varies in
the opposite way to the assimilation/observations. That is, a warm/salty anomaly systematically decreases
(due to the temperature effect) the density in the hindcasts rather than increasing it (due to the salinity effect)
as in the assimilation, leading to the negative correlation skill for density.

The strongly negative skill in Labrador Sea volume-averaged top 500 m density has implications for the
skill in the sea level variability in this region, which is poor despite the good skill in ocean heat content
(cf., volume-averaged temperature in Figure 2b). The skill in dynamic sea level (DSL) falls away similarly to
near-surface density (Figure 2b). This is not surprising as \(\rho_{500}\) and DSL are well correlated in this region in both
the assimilation \((r = -0.88, \text{as density increases sea level goes down})\) and hindcasts \((r = -0.89)\). Although DSL
depends also on the deep, temperature-driven ocean, the majority of the annual variability in temperature,
salinity, and density exists in the top 500 m, explaining the strong link between \(\rho_{500}\) and DSL (supporting
information Figure S1b). As such, we attribute the poor skill in DSL in this region to the poor skill in density,
which is itself due to the incorrect simulation of the dominant component of density variability.

The negative skill in DePreSys3 for density/DSL in the Labrador Sea region is likely to impact the ability of the
model to correctly simulate the evolution of NASPG dynamics, such as the gyre circulation and AMOC. Indeed,
the skill of the hindcasts in predicting the assimilation AMOC at the southern edge of the NASPG at 45°N
declines similarly to both density and DSL, becoming negative at lead times longer than 2 years (Figure 2b).
Although there are many possible reasons for a loss of skill in ocean dynamics — relating to, for example, the
assimilation methodology or deep ocean drifts — the location (NASPG), magnitude, and timing of this AMOC
skill loss are consistent with it being driven by the switching of the Labrador Sea density drivers that we have
investigated. This rapid loss of North Atlantic AMOC skill has implications for both decadal predictions and
longer-term projections, as discussed next.

4. Discussion
Despite the poor correlation skill in density, DSL, and the AMOC, skill in heat content in the Labrador Sea
remains high (Figure 2b) for the first 5 years, as does skill in sea surface temperatures in the NASPG (not shown),
again likely due to persistence as well as the long-term surface warming trend. However, while this may be the case on prediction timescales of several years, it is not clear to what extent incorrect simulation of ocean dynamics might be expected to affect the reliability of heat content/surface temperature projections on longer timescales, particularly as Labrador Sea signals gradually reach the lower latitude AMOC. Indeed, on multidecadal to centennial timescales, ocean dynamics have been linked to potential climate tipping points with significant global climate impacts [McManus et al., 2004; Mecking et al., 2016]. As such, our results suggest caution when interpreting the likelihood of the North Atlantic climate system to exhibit (or not) significant long-term changes related to ocean dynamical changes, for either this climate model (GC2) or other models with temperature-dominated interannual density variability in the near-surface Labrador Sea [Menary et al., 2015a].

A previous version of this prediction system, DePreSys1, has good skill in predicting ocean heat content in the NASPG [Robson et al., 2012]. It also has good skill in predicting deep density in the NASPG, and this density has been presumed to link with the ocean heat content through the AMOC modulating heat convergence into the region [Robson et al., 2012; Yeager et al., 2012; Hermanson et al., 2014]. DePreSys1 is based on the HadCM3 climate model [Gordon et al., 2000], which, using the same analysis of density components as previously, has salinity-dominated density variability in the Labrador Sea in its control simulation (Figure 2a, right-hand side). As such, forecasts with DePreSys1/HadCM3 are unlikely to switch Labrador Sea density drivers after initialization, as was the case with DePreSys3/GC2. This may contribute to the ability of DePreSys1 to model the drivers of ocean heat convergence into the NASPG [Robson et al., 2012]. Note, however, that the dynamics in the HadCM3 model are still likely to be a poor representation of the real-world dynamics. Amongst other things, these are driven by poorly constrained deep ocean densities and unresolved topographic features as well as narrow boundary currents that are not well represented in the 1.25° resolution ocean model of HadCM3.

5. Conclusions

The North Atlantic subpolar gyre (NASPG) is an important region for the initialization of multiyear climate predictions [Dunstone et al., 2011]. An important subregion of the NASPG is the Labrador Sea, in which the dominant component of interannual density variability has been shown to differ amongst climate models with potential impacts for the character of ensuing interannual/decadal ocean variability [Menary et al., 2015a]. We have investigated the dominant component of interannual top 500 m density variability in the Labrador Sea in optimally interpolated observations (EN4) and a prediction system (DePreSys3). We find the following:

1. Over the period 1960–2013, EN4 and the DePreSys3 assimilation show similar interannual variability in volume-averaged density over the top 500 m of the Labrador Sea ($\rho_{500}$) as well as similar variability in the temperature ($T_{500}$) and salinity components ($S_{500}$) of the density variability.
2. Both EN4 and the DePreSys3 assimilation suggest that top 500 m interannual $\rho_{500}$ variability is due to salinity ($S_{500}$), with temperature ($T_{500}$) opposing these changes. However, the recent trend to lighter waters since around 1995 appears to be temperature driven [Kieke and Yashayaev, 2015].
3. Over the same region, the climate model (GC2) upon which DePreSys3 is based has temperature-dominated density variability and freely evolving hindcasts using DePreSys3 switch to temperature-dominated interannual density variability within 2–3 years.
4. The switch from salinity-dominated to temperature-dominated density variability is due to the changing magnitude of temperature and salinity variability, rather than changes in the mean state. Salinity variability appears to be damped in the DePreSys3 hindcasts compared to either the assimilation or EN4.
5. There is high correlation skill in volume-averaged temperature ($T_{500}$) and, despite the changing character of salinity variability, also high skill in volume-averaged salinity ($S_{500}$) in the Labrador Sea. However, the switch from salinity-dominated to temperature-dominated interannual density variability results in strongly negative correlation skill in $\rho_{500}$ in the same region. This is also consistent with poor DSL skill in this region and similarly poor skill in the AMOC at 45°N.

Poor skill in density/DSL affects NASPG dynamics and impacts the AMOC, which raises concerns about future predictions and projections of AMOC variability — and any dynamical contribution to future trends — based on models that have temperature-dominated near-surface density variability in the Labrador Sea (primarily those with warm/salty mean state biases [Menary et al., 2015a]). To further understand and improve this
model (and all models), sustained ocean observations of integrated properties such as temperature/salinity as well as their fluxes (in order to more accurately pinpoint poorly represented processes within the models) are paramount. Programs such as the “Overturning in the subpolar North Atlantic Program” (OSNAP) aim to achieve this.

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