Supporting Information for "Delayed recovery of the Irminger interior from cooling in 2015 due to widespread buoyancy loss and suppressed restratification"

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Introduction

In this supporting information document, the reader will find an in-depth description of the analysis methods used to come to the results shown in the main text: calculation of the mean hydrographic Irminger Sea sections (Text S1); definitions of the Irminger interior and Irminger Current regions (Text S2); calculation of the regionally averaged, upper ocean density time-series (Text S3); quantification of the recovery of the Irminger interior (Text S4); and identification of the dynamics driving the Irminger gyre recovery (Text S5). The information provided here is essential to allow others to reproduce the work presented in the main text.

Text S1. Mean Hydrographic Sections

Three composite summertime potential density sections along AR07-E in the Irminger Sea are created from the hydrographic data to show the change in structure over the study period (Fig. 1 (b, c, d)). First, for each cruise, temperature and salinity profiles are interpolated onto a regular 2D grid (0.5 ^{o}E horizontal spacing, 10 m vertical spacing) and used to calculate potential density referenced to the surface using the Thermodynamic Equation of State - 2010 (TEOS-10). Cruises are then grouped by year, based on whether strong convection occurred during the following winter season (pre-strong convection: 2010, 2012, 2014; during strong convection: 2015 and 2016; and post-strong convection: 2018, 2020, 2022) and averaged in time. Note that a 2010 occupation was used in the pre-strong convection average as the data from the 2011 occupation of the AR07-E section is unmerged on the CCHDO database and the authors only recently became aware that the line had been occupied that year.

Text S2. Definitions for regional averages

Regional averages are used to track changes in the Irminger interior and the Irminger Current (IC). The interior is defined as the region where the time-mean mixed layer depth (MLD) is deeper than 650 m during months when the MLD was at least 1000 m somewhere in the Irminger Sea, with a cutoff at 59 ^{o}N to the south, similar to Sterl and de Jong (2022) (Fig. 1 (a), red crosses). At each grid-point, the MLD is defined as the depth at which the potential density referenced to the surface is 0.03 kg.m^{-3} greater than mean potential density in the upper 30 m. The IC is defined as the region on the eastern boundary where the horizontal density gradient at 300 m is steepest and the EKE is highest (Volkov, 2005; Fan et al., 2013; Sterl & de Jong, 2022) (Fig. 1 (a), magenta crosses).

Text S3. Density time-series

A time-series of potential density is produced for the interior and IC using the Roemmich and Gilson product (RG product) (Fig. 2 (a, b)). First, vertical profiles of temperature and salinity at each RG product grid-point are linearly interpolated onto a standard 10 m vertical grid and potential density referenced to the surface is calculated using TEOS-10. Second, a time-series of area-averaged potential density profiles is calculated for the interior (Fig. 1 (a), red crosses) and IC (Fig. 1 (a), magenta crosses) by averaging all the grid-points in each defined region on all depth-levels for each time-step. Additionally, a time-series of the MLD in the interior is estimated using the time-series of area-averaged potential density profiles (Fig. 2 (a), black dashed line). For each profile, the MLD is the depth at which the potential density is 0.03 kg.m^{-3} greater than mean potential density in the upper 30 m.

Similarly, a time-series of the depth-integrated buoyancy content in the 100-1000 m layer is calculated for the interior gyre and IC using the RG product (Fig. 2 (c)). Vertically interpolated profiles of temperature and salinity at each RG product grid-point are used to calculate in situ density using TEOS-10. A time-series of area-averaged in situ density profiles is then calculated for the interior and IC by averaging all RG grid-points in each defined region on all depth-levels for each time-step. Finally, the buoyancy content within the interior, B_{int}, and IC, B_{ic}, is calculated using Eq. (1).

Text S4. Quantifying gyre recovery

To determine the rates of recovery of the interior and IC the linear trend in B_{int} and B_{ic} is calculated during three distinct time periods from January 2011 to December 2022. The three periods are: pre-strong convection, from January 2011 to March 2015; during strong convection, from April 2015 to March 2018; and post-strong convection, from April 2018 to December 2022. The rate of recovery for each time period is estimated for each region using a Least Squares regression of a linear trend with a seasonal cycle of B_{int} and B_{ic}; see Eq. (2). The standard error in the slope, m, is given by the square root of the variance about the mean (Wunsch, 1996), assuming Eq. (2) is the correct model to fit the data and that there is no correlation between the noise in the different model-fitting equations.

Text S5. Identifying dynamics driving gyre recovery

The seasonal restratification of the interior is quantified by the buoyancy gained in the interior over the restratification period. The restratification period is defined as the time from minimum B_{int} to maximum B_{int} each year such that the buoyancy gain during restratification is $B_{int}^{gain} = \max(B_{int}) - \min(B_{int})$ (Fig 3 (b, c)). This allows the starting and ending months of the restratification period to vary from year to year. We note that alternatively defining the restratification period to be between specified months, eg. April to November, would only change the magnitude of B_{int}^{gain} each year and not the signal of interannual variability. B_{int}^{gain} used here is similar to the difference in Stratification Index used by Sterl and de Jong (2022) or Convective Resistance used by Frajka-Williams, Rhines, and Eriksen (2014), differing by a factor of $\frac{g}{\rho_0}$ and using in situ density rather than potential density.

The relationship between the seasonal dynamics and the multi-year recovery of the gyre is investigated by comparing the buoyancy gain during restratification to the horizontal buoyancy gradient and the EKE. First, the horizontal density gradient across the IC is approximated by differencing the buoyancy content between an inner point (x1, 59.5 ^{o}N, -35.5 ^{o}E) and an outer point (x2, 58.5 ^{o}N, -31.5 ^{o}E) of the IC (Fig. 1 (a)). Using Eq. (1), B_{x1} and B_{x2} are calculated using the single grid-point in situ density profiles and differenced at each time-step, $\Delta B_x = B_{x2} - B_{x1}$ (Fig 3 (a)). Following Spall (2004) and Straneo (2006a), we take ΔB_x at the start of the restratification period each year (Fig. 3 (a), circles) and square it, ΔB_x^2 (Fig. 3 (b)). The square is taken as the eddy-flux of buoyancy to the interior is set both by the amount of eddies generated (which, in the case of baroclinic instabilities, depends on the horizontal buoyancy gradient) and the buoyancy content of the eddies relative to that of the interior (Spall, 2004; Straneo, 2006b).

Second, we quantify the regional EKE by spatially averaging all AVISO EKE grid points within the IC region (EKE$_{ic}$, Fig. 1 (a)). The time-mean of EKE$_{ic}$ is then taken over the restratification period each year (EKE$_R$, Fig. 3 (c)). We note that this spatially-averaged EKE is different to that used by Sterl and de Jong (2022), which averages EKE from the Reykjanes Ridge to the edge of the deep convection region to ensure that eddies being considered made it into the interior, but only along the AR07-E line. The area used in our study has a much greater north-south extent but a narrower east-west extent to focus on what is assumed to be the eddy-generation region. Both spatial-averages of EKE produce the same pattern of variability despite the differing definitions.

Finally, we quantify the relationship between ΔB_x^2 and B_{int}^{gain} and EKE$_R$ and B_{int}^{gain} by the linear correlation, r$_{Bx}$ and r$_{eke}$ respectively. r$_{Bx}$ is indicative of how much buoyancy gain in the interior is provided by eddies resulting from baroclinic instabilities, following Straneo (2006a). r$_{eke}$ is indicative of how much buoyancy gain is provided by any mesoscale eddies, following Sterl and de Jong (2022). Any difference between r$_{Bx}$ and r$_{eke}$ is indicative of how much eddy-activity is due to processes other than baroclinic instabilities, as well as the error in the estimates.

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