Response to reviewer #2 on manuscript egusphere-2022-1090 titled "Temporal and spatial evolution of bottom-water hypoxia in the Estuary and Gulf of St. Lawrence". Comments posted Dec 9, 2022.

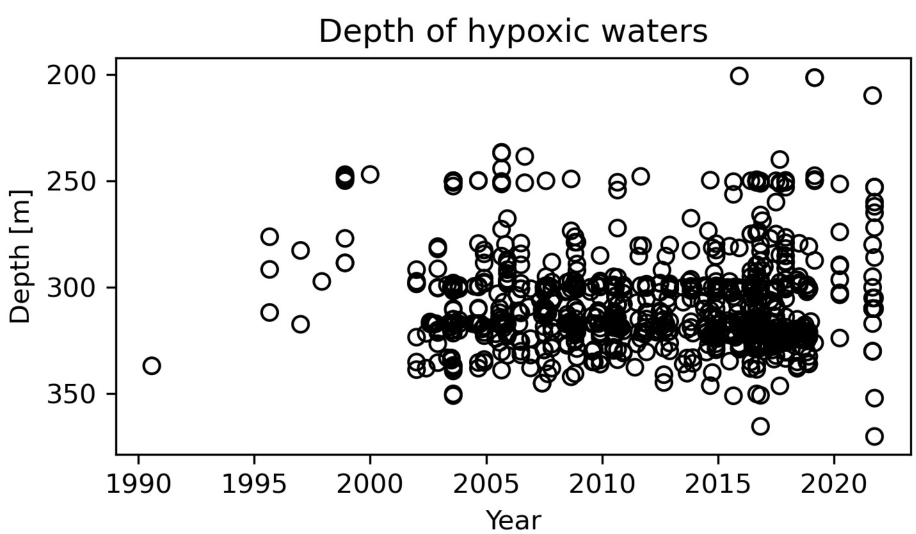
Note that many of our responses to RC2 are derived from our answers to RC1 since very similar comments/recommendations were made by both reviewers.

RC2: I found this to be a clearly written paper that efficiently reports a new piece of science around hypoxia in the system studied. My comments are primarily made to encourage the authors to add more detail to some of the methods and many of the figure captions, so some of the key details are clearly communicated.

We thank the reviewer for his(her) supportive and helpful comments.

RC2: Figure 2: Are these concentrations for all samples collected, or from a consistent timeframe? It is worth specifying that here.

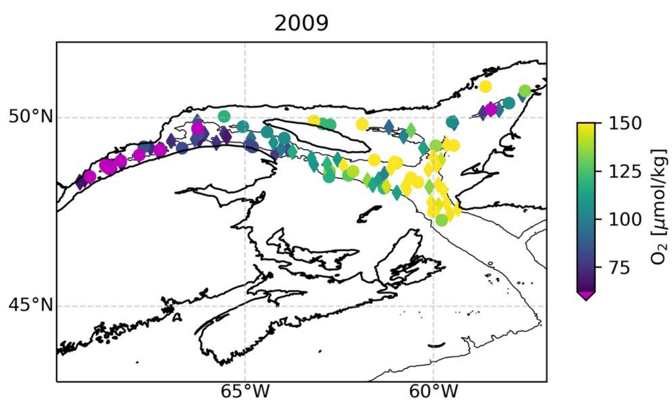
We agree with the reviewer that Figure 2 and its caption were confusing. Figure 2 shows the lowest dissolved oxygen concentrations at all the stations sampled in a given year, possibly from different surveys, along the Laurentian Channel, between 1995 and 2021. We aggregated the data for individual years, irrespective of the sampling times, to focus on the yearly trends. Most of the stations were sampled in the summer, with winter surveys in recent years (2018, 2019, 2020). We will modify the manuscript to explicitly indicate that the data are aggregated per year and that the maps show data from different surveys. We will also substitute Fig. 3 for a version that aggregates the data per season instead of yearly (see below). We could also include a new inset showing a histogram of the number of stations sampled every month from 1995 to 2021.



New version of Fig. 3, where the data are aggregated per season.

In addition to the changes related to sampling time, we modify Figure 2 to better represent the sampling depths. The figure shows the lowest sampled dissolved oxygen (DO) concentration, for any station for samples deeper than 200 m. Hence, at some stations, the measurement shown might have been sampled above the hypoxic layer. To avoid further confusion, we will use different symbols to identify samples shallower than 250 m, and thus highlight that the non-hypoxic waters (DO > 62.5 μM) are found at shallower depths. For example, in the 2009 map shown below, most of the blue stations in the estuary are diamonds, which identify samples recovered between 200 and 250m, while circles show samples collected below 250 m.

To better explain the data aggregation and to include this new information, we will modify the Fig. 2 caption to the following:
"Maps of all dissolved oxygen concentrations for samples collected in each year, since 1995, for every station deeper than 200 m. The color indicates the lowest oxygen concentration sampled over the water column. The symbol indicates if the deepest sample is located between 200 and 250 m (diamond) or below 250 m (circle). Hypoxic waters are represented in magenta. The thin black lines delineate the 275 m isobath."



RC2: Line 132: Perhaps replace "alarmingly fast" with "rapidly"? The current language reads a little awkwardly and is somewhat sensational.

We will tame down the vocabulary and substitute "alarmingly fast" by "rapidly" in the revised manuscript. Irrespective, after more than 20 years of near status quo, the sudden decrease in minimum dissolved oxygen (DO) concentrations is alarming. According to more recent measurements (September 2022), minimum DO may have dropped further to 27-30 μM.

RC2: Line 134: Is strikes me that you could argue that temperature rose rapidly in the past two years (as oxygen declined rapidly), but you really only speak to the progressive longer term trend here. This comment is also relevant in the conclusions on line 216.

This is a good point. As the minimum DO concentrations decreased rapidly, the water temperature also increased quickly, from 5.6 to 6.2^{0}C in the same parcel of water, between 2018 and 2021, reaching in 2020 nearly 7^{0}C in the western Gulf of St.

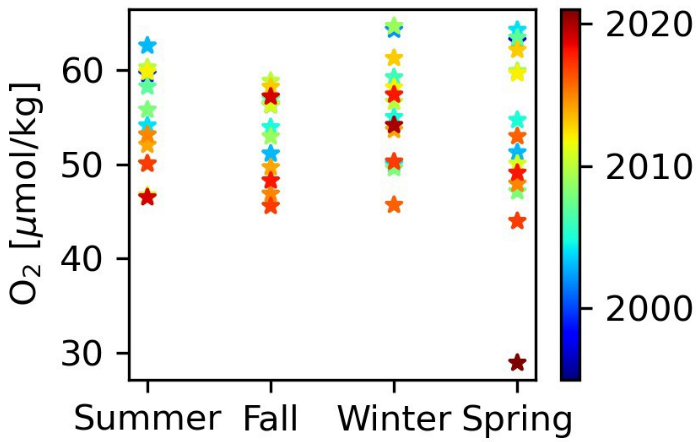
Lawrence. We will add this information in the revised manuscript at line 134: “bottom-water temperatures in the LSLE and the GSL have increased progressively from ~3°C in the 1930’s to nearly 7°C in 2020, **thus showing a rapid 1°C increase from 2019 to 2020**.”
At L216, we will change “bottom-water temperatures have increased steadily” for “bottom-water temperatures increased by one degree in only one year”.

RC2: Figure 4: What does the grey area in top panel represent?

The grey band is a visual guide and crude estimate of the temporal trend of the minimum bottom-water oxygen concentrations in the Lower St. Lawrence Estuary over the period of available field measurements.

RC2: Figure 5: Can you specify when these samples were taken each year? Is it possible that they fluctuate enough over the season that a snapshot might miss some intra-seasonal variations? If so, this would be a relevant discussion point to communicate some of the uncertainty in the study.

Like Figure 2, this figure shows an aggregation of all samples taken in any given year. We will modify the caption to indicate the periods (days and months) over which the data presented in Figure 5 were acquired in the revised caption. Most of the surveys were conducted in spring and summer, winter surveys were only conducted on three consecutive years in recent years (2018, 2019, 2020), and the data were aggregated per year in Figs 2, 3 and 5. Nevertheless, beyond the mean annual variations, no distinct seasonal variations could be discerned. This is not unexpected because the deep, hypoxic waters, are isolated from the atmosphere by the Cold Intermediate Layer. Only the spring bloom of autochthonous organic matter could affect deep oxygen levels on a seasonal scale, but the available data show no consistent seasonality (see figure below in which each coloured star represents a given year).
We will modify the introduction to include this information. We will modify L69-70 from “During most of the ice-free season, the water column of the LSLE can be described as a three-layer system on the basis of its thermal stratification.” to “The LSLE is a strongly stratified system that can be described as a three-layer system.”, and we will add the following at L74: “bottom layer (>150 m deep) flows sluggishly landward, **isolated from the atmosphere** (Dickie & Trites, 1983), for 4 to 7 years from the continental shelf-break to the head of the Laurentian Channel (Bugden et al., 1991; Gilbert, 2004). ”
As mentioned above, we will also explicitly indicate that the data are aggregated per year, and justify this approach by noting that available data show no clear seasonality and that this study focuses on yearly variations. To further justify our assumption, we will substitute Fig. 3 for a version in which the data are aggregated monthly instead of yearly.



RC2: Figure 6: Is there an explanation why there is 20-50% LCW fraction in the ~275 m water between 200 and 500 km? The only reference to this figure is that LCW is now almost null, but this seemingly residual or preserved LCW fraction was not discussed, and I think it should be.

Since the bottom waters require 4-7 years to transit from the mouth of the Laurentian Channel to its head (at the head of the LSLE), the layer of 20-50% LCW that appears at ~250m depth at the landward part of the transect could be bottom water that is several years older and richer in LCW than waters now entering the Gulf at Cabot Strait,.The null LCW fraction seen above and below the LCW-enriched layer is expected, since below we find the NACW, and above, the CIL. The presence of the LCW, distinct for the NACW, was first resolved in Jutras et al. (2020b) upon a more refined e-OMP analysis of available data. The analysis revealed that the LCW and NACW that make up the bottom waters of the Laurentian Channel are not perfectly mixed and a layer of water richer in LCW sits on top of a NACW-rich layer in the Lower St. Lawrence Estuary (LSLE). We agree that a discussion of the uncertainty of this method is missing, and we will add a few sentences on this subject in the text. We will also add an explanation on the observed 20-50% LCW fraction either in the caption or the main text of the manuscript.

RC2: Line 160: Are there data to report here about organic matter and nutrient exports? Minimally it would seem relevant to report a quantitative change, or maximally a figure of the long-term data.

A limited historical record (1995-2012) of organic matter and nutrient exports from the St. Lawrence River to the Upper St. Lawrence Estuary was published by Hudon et al. (1997), but no clear trend could be identified over this period. Unfortunately, we could not find a multi-decadal time series of nutrient loading for the St. Lawrence River, as is available for the Mississippi River (Turner et al., 2007). The Mississippi River record reveals a large anthropogenic increase in nutrient loading since about 1970. Given the geographic proximity of the two drainage basins, and the similar agricultural practices and industrial activities, it would be reasonable to assume that nutrient loading to the St.

Lawrence River has also increased over the last decades. Indirect accounts of nutrient loading certainly support this hypothesis, like the increase of nitrogen and phosphate fertilizer sales in Quebec and Ontario (Statistics Canada, 2018), as well as the, respectively 3.8 to 4.5-fold, increase in the estimated net anthropogenic P and N inputs to watersheds of the St. Lawrence Basin over the last century (Goyette et al., 2016). This impact of nutrient loading to the Lower St. Lawrence Estuary (LSLE) was addressed in detail in Jutras et al. (2020a) in which the authors present a three-layer box model and budget of nutrients in the LSLE. In this paper, they conclude that the majority of nutrients delivered to the LSLE originate from upwelling of nutrient-rich waters at the head of the channel. Whereas bottom-water nutrient concentrations have increased noticeably since at least the early 1960's, they reached near steady-state values in the 1990's. We will detail these findings in the revised manuscript instead of simply citing these references at the end of L161.

RC2: Line 185-190: I appreciate that the methodology has been presented before (Jutras et al. 2020b) to partition the delta DO among driving factors, but I think a brief explanation of the approaches here would help make this paper stand alone.

We feel that it would be unreasonable to repeat details of this methodology here as it would unduly lengthen the manuscript. The main objective of the present paper is to present the temporal variations in spatial extent of the hypoxic zone. The other objective is to highlight the sudden drop in dissolved oxygen (DO) concentrations since publication of the Jutras et al. (2020), in which the most recent data are from 2018. Identification of the mechanism responsible for this sudden drop in DO does not represent a new scientific contribution, since it is the same as for the 2008-2018 period covered in Jutras et al, (2020). Hence, no new information would come from further discussion on these causes. Alternatively, we will provide a more detailed summary of the method (i.e., e-OMP), the properties of the source/parental waters to the bottom waters of the Laurentian Channel, how their relative contributions have varied over the last few decades and why, as well as the relative contribution of in-situ (pelagic or benthic) respiration as the bottom waters flow inland from the mouth to the head of the Laurentian Channel.

RC2: Figure 8: can you express what error bars represent here? How were they calculated?

The error bars represent the uncertainty associated with the calculation of the areal extent of the hypoxic zone, as described at L110-111. The uncertainty is, in great part, a consequence of the low spatial resolution sampling, and more specifically the extrapolation of the area between the last hypoxic station and the first non-hypoxic station along the Laurentian Channel. We will add a reference to L110-111 in the revised caption.