Reaching a Tipping Point in the Subpolar North Atlantic before 2050?

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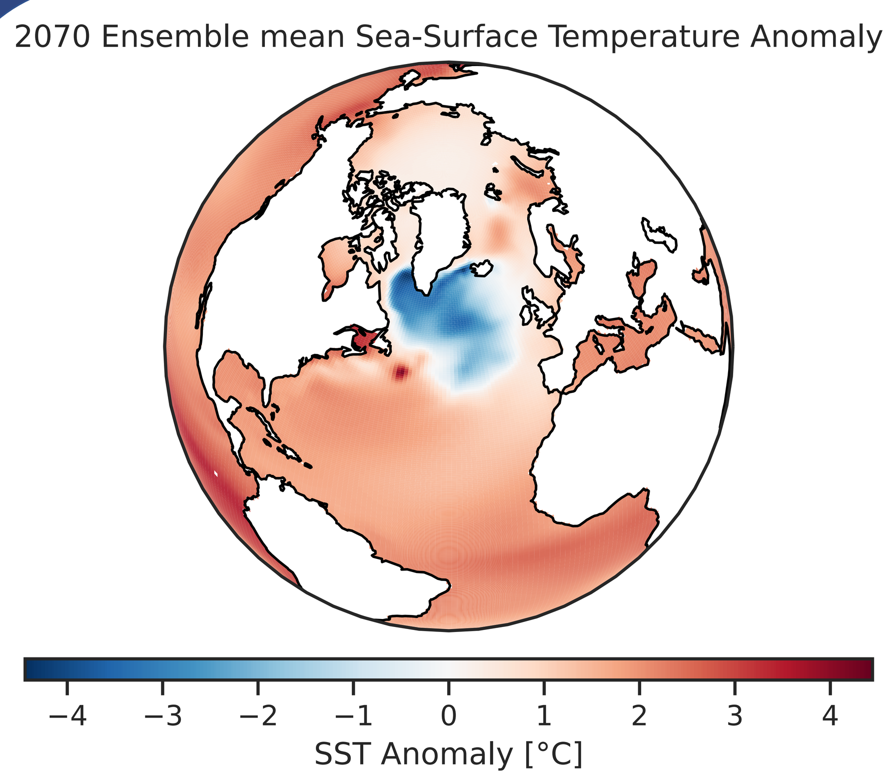

Figure 1: *Ensemble mean SST 2070 - 2000*

Introduction:

Abrupt climate change and so-called tipping elements in Earth's climate system introduce large uncertainties when predicting the evolution of our climate. The most recent study on tipping elements by Armstrong McKay et al. [2] included the subpolar North Atlantic as a system that could undergo a rapid transition to a new stable state based on the work of Sgubin and Swingedouw et al. [3,4]. They describe how a collapse of deep convection leads to the development of a strong cold Sea-Surface Temperature anomaly ***(Figure 1)***. Here, we take a closer look at the development of these events and determine the years of reaching this tipping point using the Community Earth System Model 2 Large Ensemble (CESM2-LENS).

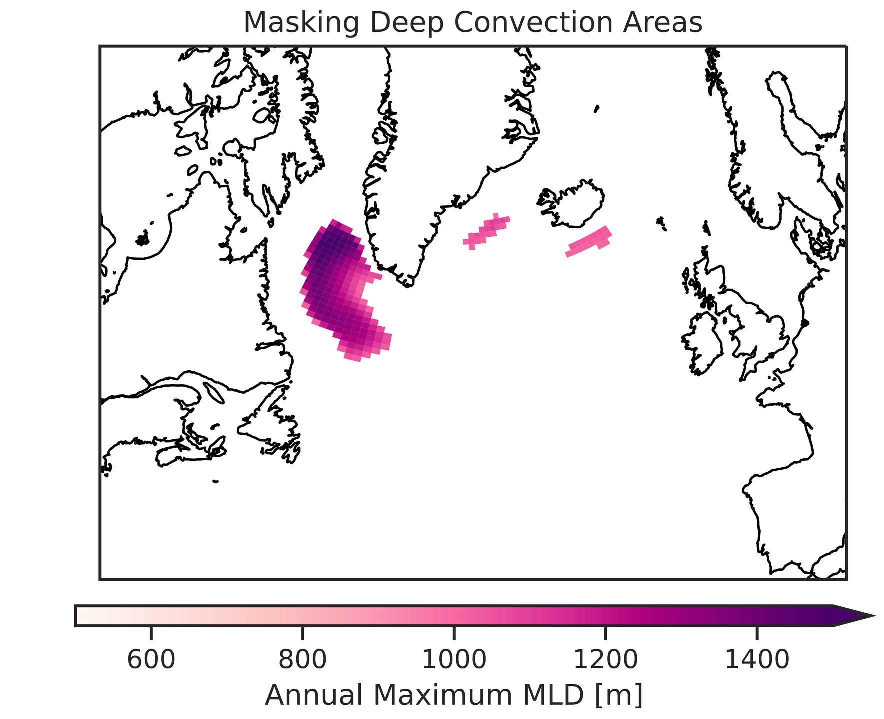

Figure 2: *SPG mask, where the annual max. MLD. exceeds 1000 m*

- **Data:**
  - CESM2-LENS forced by SSP3-7.0 containing 100 members
  - CESM2 forced by SSP1-2.6 with 3 members
  - Variables: Sea-Surface Temperature (SST)/ Salinity (SSS) and Mixed Layer Depth (MLD)
- **Determining reference region** (SPG mask)**:** In line with Sgubin et al. [3], we define the reference region as the area where the annual maximum MLD exceeds 1000 m ***(Figure 2)***. Sensitivity testing using different criteria and thresholds resulted in no changes in the results (not shown).
- **Tipping Point Identification Algorithm:** Sgubin et al. [3] identified an event as an abrupt cooling event when a 10-year SST drop exceeds three standard deviations. We changed the approach and identify abrupt cooling events when exceeding three standard deviations in the 10-year rate of change of the SST time series.

Tipping Identification Results:

- Using the described tipping point identification algorithm, we find that in the CESM2-LENS the SPG region experiences a collapse of deep convection and the corresponding abrupt cooling on average in year 2042.
- Some ensemble members tip already in year 2016, but no member tips after year 2070 with all members experiencing an abrupt cooling event at some point

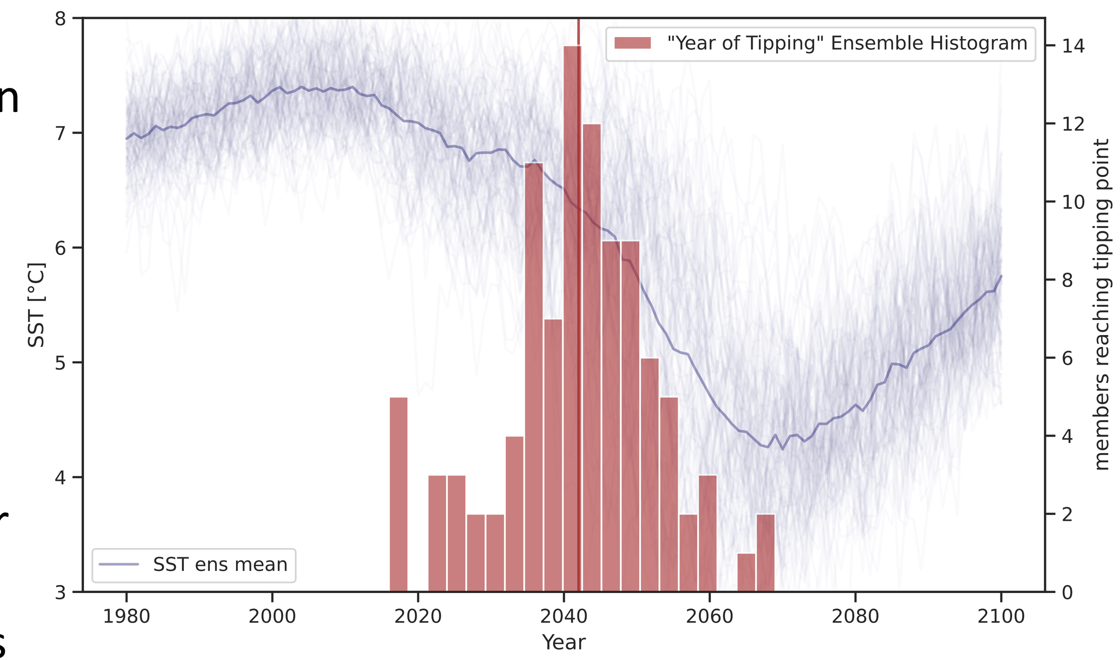

Figure 4: *Light blue lines show SST as in Figure 3. Red Histogram shows the distribution of "Year of Tipping" for each ensemble member, indicating when the tipping event begins. Red vertical line shows "Year of Tipping" ensemble mean, being year 2042.*

Abrupt Changes in the SPG:

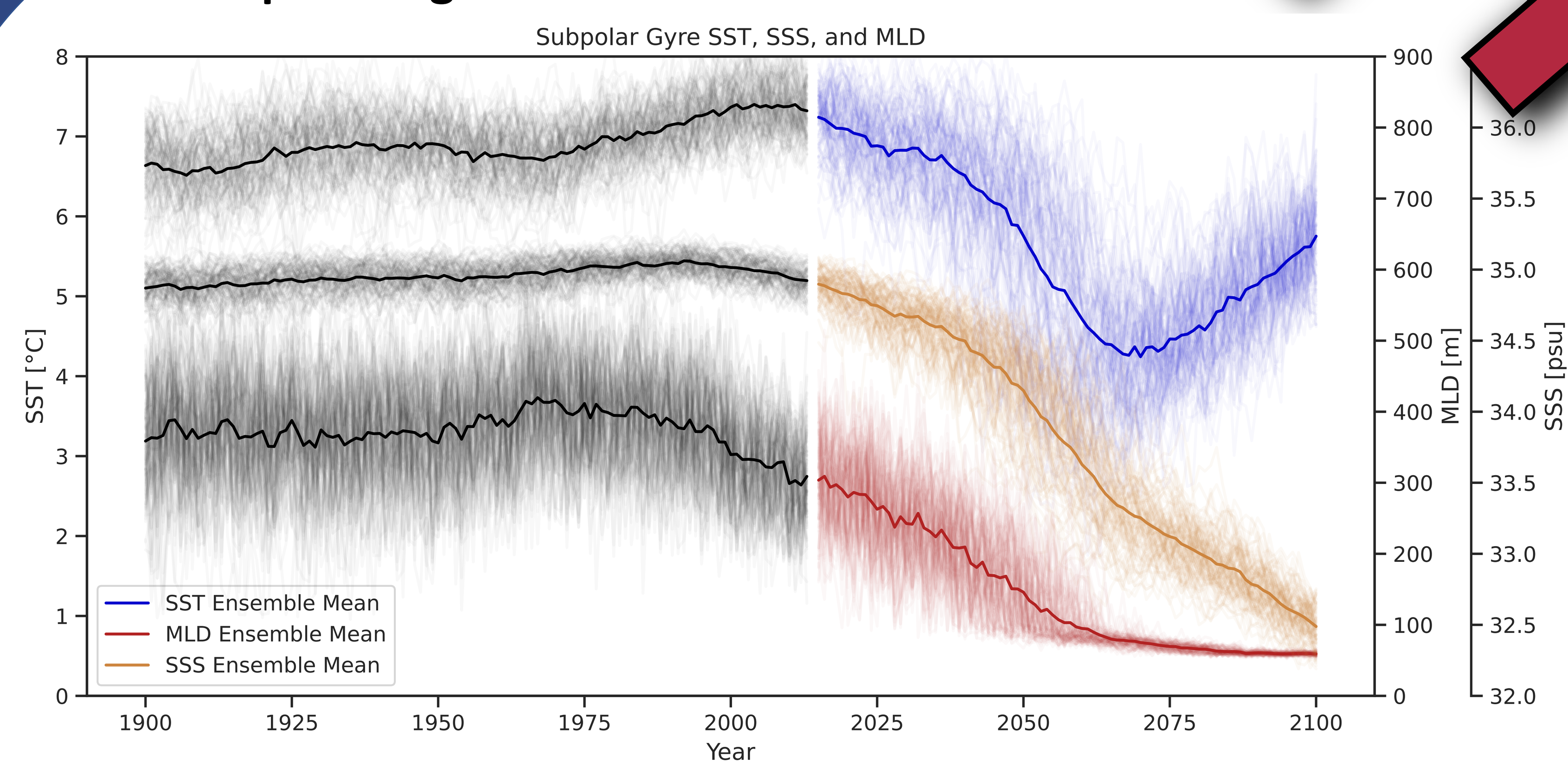

Figure 3: SST, SSS, and MLD averaged over the SPG mask (Figure 2). The historic data in black from 1900-2015, and the data for SSP3-7.0 in blue for SST, in orange for SSS, and in red for MLD from 2015-2100. Thin lines are ensemble members, thick lines are ensemble mean.

- **MLD:** Until around 1975 the SPG MLD is stable. After 1975 it starts declining and falls below 100m of depth in the whole ensemble by year 2065. Note that also the ensemble spread reduces significantly and the MLD does not recover after its collapse.
- **SSS:** Stable until year 2000, after which a slow decline starts and gets more rapid with increased ensemble spread between 2040 and 2060. After 2060 SSS declines further with a slight decrease in the slope steepness and a smaller ensemble spread compared to the prior two decades.
- **SST:** SPG SSTs are increasing up until 2015. Then a gradual decline is visible before a more rapid drop bigger than 2°C between 2040 and 2060 happens. After 2060 SSTs increase again at a higher rate compared to initial temperature rise in the historic data.
- **Explanation:** Deep convection brings warmer waters to the surface where they loose heat to the atmosphere. If the MLD is shallow, a smaller body of water looses heat and therefore experiences stronger cooling, resulting in a stronger cold SST anomaly. After deep convection ceases to exist in the SPG and the atmosphere being significantly warmer due to strong forcing, the smaller body of water heats up again at a stronger rate than prior to the cooling.
- **SST or SSS? :** Correlating temperature/salinity profiles with potential density data lead to the conclusion that the density anomaly that results in the collapse of deep convection is most likely driven by a freshening of the SPG. This gets more intuitive when considering that colder water is more dense and should have a positive effect on the MLD.

Other forcing Scenario:

When carrying out the same analysis for a weaker forcing scenario, we find that CESM2 forced by SSP1-2.6 reaches the tipping point where an abrupt cooling is inevitable significantly earlier.
This poses the question what exactly the main drivers for a convection collapse and freshening of the SPG are!

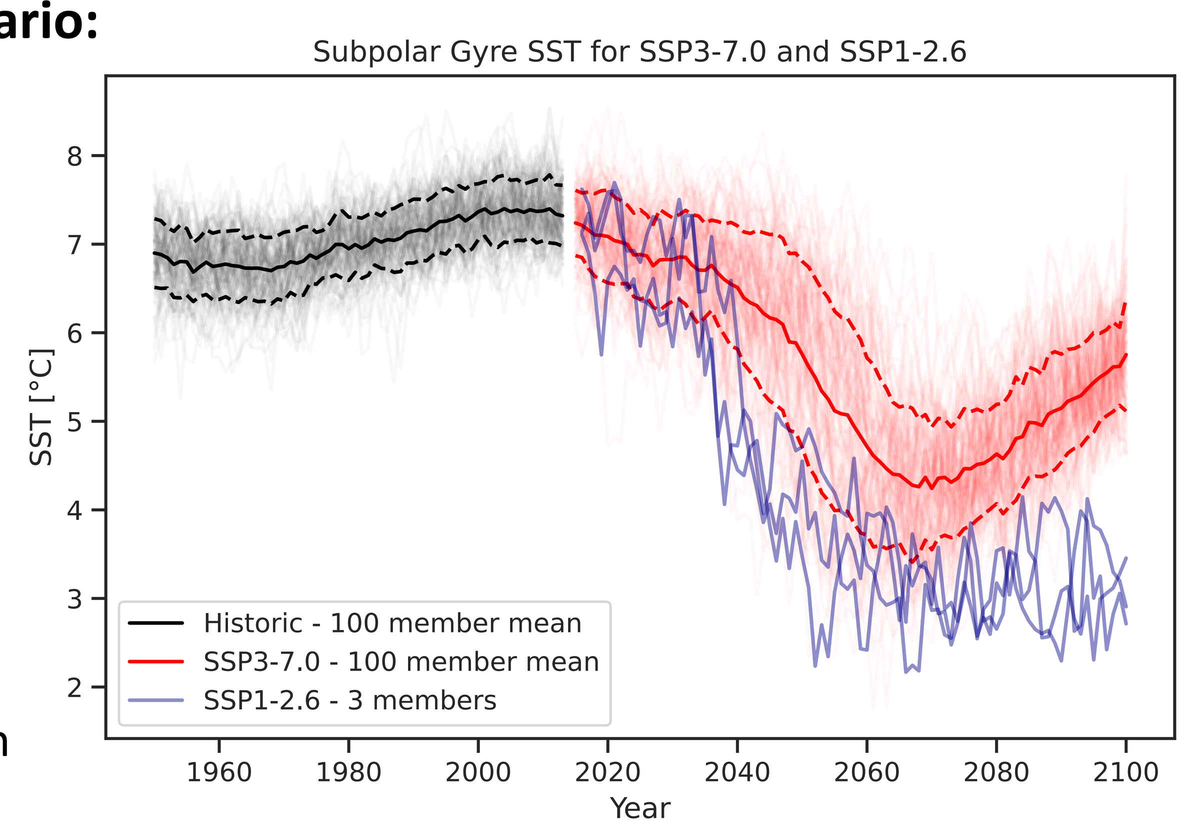

Figure 5: *SST as in Figure 3 (red), but including one ensemble standard deviation (dashed lines). Additional, three CESM2 runs forced with SSP1-2.6 are added.*

Take Home Messages:

- Abrupt cooling events happen in all ensemble members and all forcing scenarios in CESM2
- The convection collapse leading to the abrupt cooling is mainly driven by a freshening of the SPG
- A weaker forcing seems to lead to an earlier collapse of deep convection

What's next?:

Due to the weaker forcing resulting in an earlier convection collapse, another threshold is likely to have been passed prior to 2015 where CESM2 is starting to be forced by the different SSP scenarios. Some results (not shown) point into the direction that strong and abrupt changes in the Gyre circulation play a significant role in the overall freshening of the subpolar North Atlantic.

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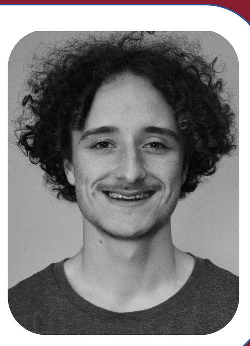

References:

(1) J. Müller, Abrupt Climate Change in the subpolar North Atlantic: Drivers and Impacts, Master's Thesis (in progress)
(2) Armstrong McKay, David I et al. (2022). "Exceeding 1.5° C global warming could trigger multiple climate tipping points". In: Science 377.6611, eabn7950.
(3) Sgubin, Giovanni et al. (2017). "Abrupt cooling over the North Atlantic in modern climate models". In: Nature Communications 8.1, pp. 1–12.
(4) Swingedouw, Didier et al. (2021). "On the risk of abrupt changes in the North Atlantic subpolar gyre in CMIP6 models". In: Annals of the New York Academy of Sciences 1504.1, pp. 187–201.

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