Summary of existing and forecasted climate change across the north Atlantic relevant to salmon marine ecology

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North Atlantic Salmon populations have generally shown a decreasing trend since the 1980s. This coherent large-scale decline both in productivity and abundance across Atlantic salmon stocks points toward changes in the marine phase of salmon as a governing factor. Coincident with the decline in salmon, the North Atlantic has become warmer since the 1980s, there have been marked changes in the circulation and associated changes in hydrography, nutrients, primary production. Temperature affects growth, survival, and maturation of salmon during the marine phase (Beaugrand and Reid 2003; Friedland *et al.* 2005; Todd *et al.* 2008). The focus of this presentation is to review observed and projected climate change scenarios for the 21st century, with a focus on habitat changes in the North Atlantic of relevance for salmon. The more specific questions related to the biology effect related to salmon will be covered in accompanying presentations.

The North Atlantic plays a key role in redistribution of global heat. There is a much larger transport of heat to the Arctic via the North Atlantic compared to the Pacific. This explains the northward slanted isotherms toward northern Europe. It also explains why the Atlantic salmon has a much shorter latitudinal range in the western (US Canadian) compared to eastern north Atlantic. On the western side it spans latitudes of about 40-50ºN (1000 km) from the US to Canada while on the European side it spans latitudes from about 45 – 70ºN (2500 km).

The North Atlantic climate is observed to vary over a broad range of time scales. The longest period resolved by instrumental records is the Atlantic Multidecadal Oscillation (AMO) with period of order 60-70 years (e.g. Mann *et al.* 2020). If this is an intrinsic period of the North Atlantic climate system, e.g. related to the Atlantic Overturning Circulation, or if is simply forced by radiation change due to variability in volcanic forcing is under debate (Mann *et al.* 2020; Muller-Plath, 2020). However, regardless of mechanism, there is substantial evidence of ecosystem response generally following the AMO phasing (Drinkwater *et al.* 2013).

One main characteristic of the North Atlantic climate system is the opposite climate variability between the Greenland Labrador region and the northwestern Europe (van Loon and Rogers, 1978) with cited evidence of its existence dating back to the 18th century. Basically, this is connected to the local effect of the North Atlantic Oscillation (NAO) (Walker and Bliss 1932). The positive/negative phases of the NAO are associated with increased/decreased ocean heat loss over the Labrador Sea, while this relation is opposite for the Barents Sea. However, from the mid- 1990s, air and sea temperatures in both regions generally have been in phase, showing strong warming and reduced ice coverage. The cause of this change is related to changes in the spatial structure of the atmospheric pressure patterns, resulting in a general reduction in the importance of NAO forcing over the North Atlantic (Drinkwater *et al.* 2013).

Since the mid-1990s some remarkable changes have occurred in the North Atlantic. First, as a manifestation of a warming climate the general cooling of the Atlantic Water flowing northward to the Arctic has decreased, i.e. reduced ocean to air heat loss (Mork *et al.* 2014, 2019). The subpolar gyre, a large water mass bound by the Labrador current on the north and west and the Gulf Stream in the south and east, transitioned from a strong state prior to 1995, to a subsequent weaker state with reduced amount of relative cold/fresh subpolar water mixed into the North Atlantic Current (Hátún *et al.* 2005), and associated ecosystem response across many tropic levels (Hátún *et al.* 2009). Then during 2012 to 2016, the eastern subpolar North Atlantic underwent extreme freshening in response to anomalous winter wind patterns driving major changes in ocean circulation, including slowing of the North Atlantic Current and diversion of Arctic freshwater from the western boundary into the eastern basins (Holiday *et al.* 2020), a signal also evident in the Nordic Seas with an advective delay of some few years (Mork *et al.* 2019) that altered the water mass composition in the Norwegian Sea (Skagseth *et al.* 2022).

Since the 1980s observations show a general 1ºC warming in the upper ocean. However, a marked exception from this is in the subpolar North Atlantic that in fact has experienced slight cooling, often termed the North Atlantic warming hole or cold blob (Drijhout *et al.* 2012). The North Atlantic warming hole is associated with a decline of the Atlantic Meridional Overturning Circulation (AMOC). The warming hole is situated south of deep convection sites, indicating that it involves an adjustment of the gyre circulation. The warming hole is prominent in historical runs, where the response of the AMOC to global mean temperature is weak. In the more strongly forced scenario runs, the warming hole over the subpolar gyre becomes weaker, while cooling over the Nordic seas increases, consistent with previous findings that deep convection in the Labrador and Irminger Seas is more vulnerable to changes in external forcing than convection in the Nordic seas, which only reacts after a threshold is passed.

Figure The major ocean current systems in the North Atlantic

The main question here is how the wild salmon have responded to the North Atlantic climate variability that is observed to occur over a broad range of time scales. On the longest observed scales, the Atlantic Multidecadal Oscillation describes long-term fluctuations in annually autocorrelated sea surface temperatures with a period of about 70-80 year, that seems to have a positive correlation across tropic levels (Beaugrand and Reid 2003). Condron *et al.* (2005) suggested a shift in the AMO in the early 1990s may have deteriorated marine growing conditions for salmon and predicted that this could persist until the mid-2020s. The exact pattern in variation of the AMO appears to exert different effects on European and North American salmon stocks (Friedland *et al.* 2014).

For the North American salmon, there was a decline in abundance after 1990, and productivity declined between 1987-1996 (Mills *et al.* 2013). This period was extreme in terms of a positive NAO condition and severe condition on the northwest Atlantic shelves, but with a subsequent record drop to negative NAO conditions in 1996. Changes in salmon may be initiated by extreme changes in the environment. Further, the warming since about 2000 may have restricted southern spawning. The lack recovery for salmon when environmental conditions reverted to 1980s-like conditions points toward ecosystem changes that prohibit recovery. In Labrador Sea after 2000 there have been increases in phytoplankton production (Behrenfeld *et al.* 2006). However, these have led to an increase in small zooplankton, while lipid -rich zooplankton, and capelin have continued to decline compared to pre-1990 estimates (DFO, 2011). This points to the importance of extremes in climate conditions that change the trophic interactions that prevent rebound of salmon despite climate condition returning to more normal conditions.

For the European salmon there is substantial evidence that temperature governs growth, survival, and maturation of salmon during the marine phase (Beaugrand and Reid, 2003; Friedland *et al.* 2005; Todd *et al.* 2008). From the 1960 to 2009 pronounced declines have been noted for zooplankton (total copepods, Cal. Fin.) and euphausiids and salmon catches along with increasing trends in SST, AMO, NHT, and phytoplankton (Beaugrand and Reid 2003, 2012). These changes occur as coincident progressive steps in both the environment and the biology (Beaugrand and Reid 2012). For Norwegian salmon stocks Vollset *et al.* (2022) reported an unprecedented collapse in growth about 2005 and suggest that there are additional explanatory factors beyond physiological limitations imposed by temperature. The simultaneous changes to temperature, zooplankton, and marine growth of Atlantic salmon and subsequent decrease in size of mackerel occurred after what seemingly was a sudden reduction in the transport of Arctic water into the Norwegian Sea. This observation may suggest that the simultaneous occurrences of shifts in physical and biological measurements are driven by a bottom-up process associated with abiotic environmental changes or at least that these changes were set in motion by a shift in distribution of Arctic water in the Norwegian Sea (Skagseth *et al.* 2022). The zooplankton density and nutrients (Skagseth *et al.* 20022) is higher in Arctic water than in Atlantic water, so conveyance of food may also have declined after 2005 (Toresen *et al.* 2019; Utne *et al.* 2022). The reduced transport of Arctic water with high abundance of microzooplankton into the Norwegian Sea is therefore a plausible explanation for the shifts in post smolt growth and ecological regime (Utne *et al.* 2022). In farm-intensive areas, mortality of wild Atlantic salmon due to salmon lice may be considerable, and for survivors, the marine growth may be affected (Vollset *et al.* 2019). However, the decline in growth and decline in one-sea-winter fish that occurred in 2005 is not mainly driven by impacts of fish farms.

Given the ~post 2000s decline in salmon that has coincided with a warmer North Atlantic the question of how climate will evolve and what will be the expected effect on salmon is highly relevant. In a comprehensive modelling study Alexander *et al.* (2018) assessed changes in the mean, variability, and extreme sea surface temperatures (SSTs) using the observed greenhouse gas concentrations for 1976–2005 and the RCP8.5 "business as usual" scenario for greenhouse gases through the remainder of the 21st century. They found that the annual mean trend over North Atlantic was in the range from 0.05 to 0.5°C decade^{-1}. Forecasted SST changes by the end of the 21st century are primarily due to a positive shift in the mean with only modest changes in the variability for shelves across the North Atlantic. The SST trends are generally stronger in summer than in winter, as greenhouse gas heating integrates over a much shallower climatological mixed layer depth in summer than in winter, which amplifies the effect of greenhouse warming. However, a pronounced feature of these scenario runs is the subpolar North Atlantic where the trend was generally small, and even negative for March.

A forecasted general warming of the North Atlantic in the 21st century suggests that southern stocks across the Atlantic will decline. This would be especially true if the global general warming and extremes are even stronger over land than ocean, which may result in increased migration to northward shifting marine feeding area. At the same time, it is very likely that a generally warmer climate could provide a thermal regime allowing for salmon to occupy more northern rivers. The warming of the upper ocean is likely to increase the stratification and reduce the mixed layer depth, and phytoplankton production may increase, but again a warmer ocean may favor smaller zooplankton that again may not be beneficial as prey for fish including salmon. However, while an overall warming trend is expected, the subpolar North Atlantic is an area of large natural variability with associated changes in circulation, water masses, nutrients, and biota, that is likely to affect salmon in non-linear ways. Thus, to predict the marine condition for salmon growth and survival is a difficult task, especially given the spatial variability in how these conditions may develop across the North Atlantic. However, recent high temperatures are considered anomalous within the context of 1000s years, and this warming will continue. The Atlantic salmon will need to adapt to this warming climate, and thus changes of occupation area are to be expected in both the freshwater and marine phases.

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