Climate change and the de-oxygenation of Norwegian sill fjords

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The basin water of a sill fjord is renewed intermittently, when the density of the water at sill level in the ocean outside the fjord is high enough for it to sink down to the bottom of the fjord. How often the basin water is renewed, the renewal frequency, depends on how fast diffusion and mixing cause the density in the basin to decrease and on the variability of the density in the ambient ocean. The longer the stagnation period – the larger the total oxygen consumption and the greater the risk of hypoxic or even anoxic conditions in the fjord basin.

Here we show that:

The density, and notably the density extremes along the coast of Norway that is associated with deep water renewals in the fjords, has decreased since 1990 and this has likely led to longer stagnation periods and decreased oxygen concentrations, especially in the fjords of south-western Norway.

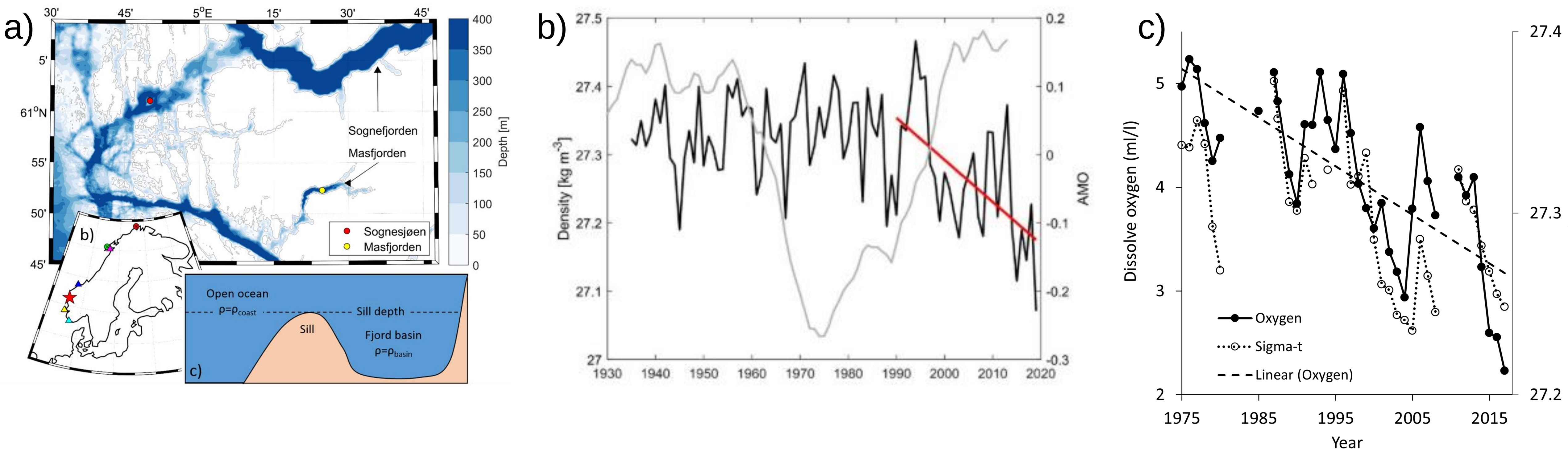

Fig 1a) Map showing the location of Masfjorden, Sognesjøen and the other hydrographic stations along the coast of *Norway*. b) Annual maximum in density observed at Sognesjøen (black line). The red line shows the trend after 1990. c) Evolution of oxygen (filled circles) and density (open circles) in the basin of Masfjorden since 1975.

Hydrographic data have been collected at 8 stations along the Norwegian Atlantic coast roughly bi-weekly since the 1930's. Six out of eight stations show (at most depths) a decreasing trend and increased variability in the annual maximum density (Fig. 1b and ref. 2) Temperature is the main contributor to the decreased density[1,3]. At the same time, we observed a decreasing trend in the oxygen concentrations of e.g., Masfjorden (Fig 1a,c, ref 1) and Byfjorden[4] (situated outside Bergen)

We use (A) a statistical approach[2] and (B) a two-layer model to asses the impact of the observed trend in density on the length of the stagnation period in Norwegian sill fjords

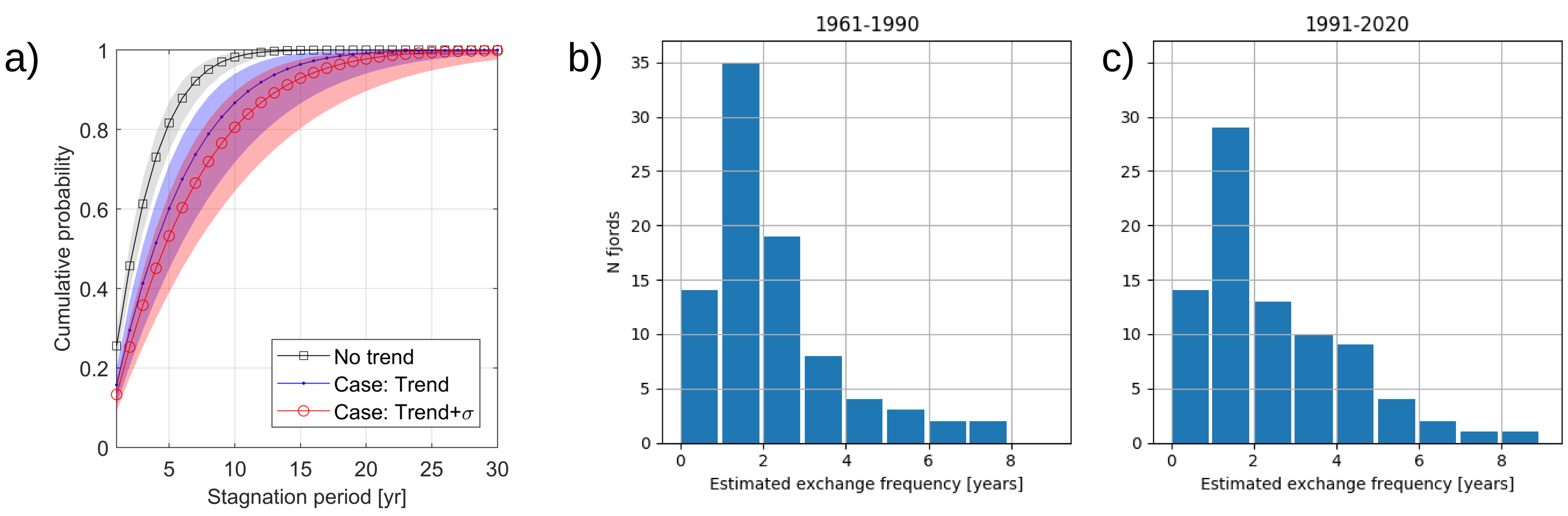

Fig 2a) Cumulative probability distribution for the length of stagnation period in Masfjorden prior to (black line) and after (red and blue line) 1990. Modelled mean length of the stagnation periods in 91 Norwegian fjords during the period b) 1961-1990 and c) 1991 – 2020.

A. The statistical approach

We assume that (i) the basin water is renewed completely when the density outside the fjord is higher than that of the fjord basin, (ii) density in the basin decreases at a constant rate D, and (ii) that the density outside the fjord varies around a mean value with a standard deviation, σ (with or without a superimposed trend, α) and apply a Monte Carlo approach to estimate the probability distribution for the length of the stagnation period given D, σ and α.

B. The two-layered model

We consider the fjord to be a two-layer system and estimate the evolution of the system and the timing of deep-water renewals using (i) observed hydrographic forcing from the nearest hydrographic station, (ii) observed tidal amplitudes, (iii) known basin and sill geometry and (iv) empirical expressions that uses i-iii to estimate decrease in the density of the lower layer with time.

Conclusions

Both approaches suggest that the mean stagnation period of many fjords in south-western Norway has increased significantly due to the observed changes along the coast – likely explaining for example the decreasing oxygen trend in Masfjorden (Fig 1c, ref 1). Values from Masfjorden, for example, suggest that the while the fjord could be expected to be anoxic 0.6 % of the time prior to 1990, this would increase to 12% of the time in post-1990 conditions.
While a few fjords experienced enhanced vertical mixing during the latter period (in the two-layer model) this was in general not sufficient to overcome the effect of the negative density trend off shore.

References
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