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# Predicting future shifts in herring spawning habitat in the North Sea

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## Summary
Herring (*Clupea harengus*) is a demersal spawner, with spawning grounds along the British coasts in the North Sea. Its timing of spawning is expected to shift (in time, location, spatial distribution) due to climate change and temperature increase. We have collated data on herring spawning areas, substrate suitability, bottom depth, current velocity and weekly bottom temperature data for the period 1960-2100 provided by a regional climate model applied in the North Sea under future climate scenario RCP4.5. We used GAMs to describe the relation between presence-absence of spawning and environmental variables. The results suggest association of spawning with temperatures 8-13 $^{o}$C, intermediate/high current velocities (0.13-3 $m^3/sec^3$) and depths 20-90 m. Model predictions under future conditions (2090s) suggest a shift towards earlier spawning in the northern spawning areas and later spawning in Downs. If the northern spawning components maintain their current spawning period, they would potentially face a narrower spatial distribution of suitable conditions for spawning. Expected egg survival given future temperature scenario suggest relatively little change, although further warming indicates a decreasing trend in survival probability. These analyses indicate how climate change could affect herring life history and ecology in the North Sea under future warming.

## Introduction
Human-induced climate change has caused temperatures to increase in the North Atlantic Ocean including areas such as the North Sea (MacKenzie and Schiedek 2007). Climate change is expected to affect individual organisms, the structure, biomass and geographic distributions of populations, and subsequently community structure (e.g., Beaugrand 2009). Climate change will also affect key physiological rates (e. g., survival) and could lead to alterations of life histories including changes in spawning time or location. The impacts of such changes for survival of the early life history stages or for population dynamics are not known, but could include changes in exposure to food or predators. Herring could be a particular vulnerable species because it spawns demersal eggs on specific substrates found only in restricted regions of the North Sea. Here, we first estimate and quantify the main abiotic variables associated with present spawning areas, and then use a regionally downscaled global climate change model scenario of temperature change in the North Sea to investigate how future temperatures could affect spawning time and location and egg survival.

## Materials and Methods
Spawning grounds were extracted from published literature and were converted to presence of eggs. Locations outside the spawning grounds but within the defined study area (North

Sea and most of English Channel) were used to define areas of absence of spawning. Bottom temperatures in the North Sea were extracted from a regional simulation model under future IPCC climate scenario RCP4.5, with uncoupled run applying boundary forcing interpolated from transient climate simulations by EC-Earth (MI model; described in Tian et al. (2015)). GAMs were used to describe the presence-absence of spawning in relation to bottom temperature during the spawning season (average for 1960-1980), depth and current velocities. Probability of presence of spawning was estimated for different weeks and areas with appropriate substrate types (Figure 1a) in past (1960-1980) and future (2090-2100) decades in order to investigate potential changes in timing and location of spawning. Survival probability of eggs was estimated under past and future conditions, using a fitted Gaussian curve to egg survival and temperature data extracted from Blaxter (1956).

## Results and Discussion

The final model included all three explanatory variables (temperature, depth, log-transformed velocity) and explained 39.3% of the deviance. Herring spawning areas are associated with temperature between 8-13 °C, intermediate-high current velocities and depths shallower than 100 m.

Maintaining their current spawning periods will be accompanied by a narrower spatial distribution of suitable conditions for spawning at the known spawning locations, especially at the northern spawning areas.

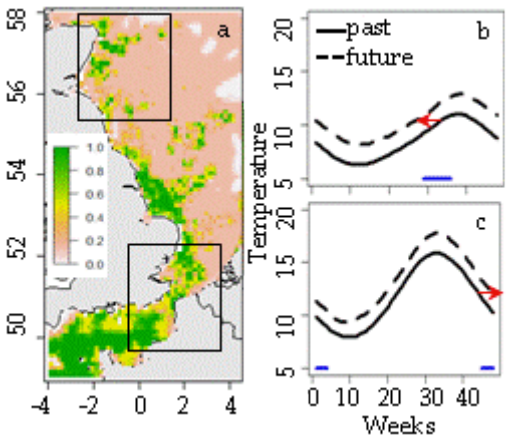


**Figure 1 a) Substrate suitability index map. b-c) Average bottom temperature per week at the Buchan (b) and the Downs (c) spawning areas in past (1960-1980) and future (2090-2100). Blue line along the x-axis indicates the spawning season per area.**

The average spawning probability per area and week indicated a general shift in the time when spawning-favorable conditions are found, assuming maintenance of the spawning locations and thermal preferences. The model predicted higher probability of spawning earlier in summer for the summer-autumn spawning components (i. e., before bottom temperatures reach seasonal maxima in early autumn), primarily because future autumn bottom temperatures become too warm compared to the populations' preferences (Figure 1b). Similarly, the southern spawning component, Downs, would be forced to spawn later in the winter (Figure 1c).

Expected egg survival given future temperature scenario suggest relatively little change, although further warming (end of century) indicates a decreasing trend in survival probability.

The variables considered here represent only a portion of the entire suite of factors that shape spawning time and locations for herring in the North Sea. The timing and location of spawning are likely long-term evolutionary tradeoffs by adults in response to seasonal/spatial variability in ecosystem conditions affecting offspring survival and lifetime fitness.

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