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Environment induced changes in krill abundance in the North Atlantic Ocean

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Summary
Sea surface temperature, sea surface salinity, NAO, surface chlorophyll *a* concentrations and timing of the spring bloom were used as explanatory variables to investigate the impacts of climate variations on krill abundance in the North Atlantic as recorded by the Continuous Plankton Recorder (CPR) survey during 1958 to 2007. On a spatial scale, the annual mean krill numbers gradually decreased from east of Greenland (Irminger Sea) to west of Faroe Islands, indicating that the Irminger Sea may serve as a high productive area or population centre of krill in the North Atlantic. On a temporal scale, a general and significant decreasing trend in yearly mean krill numbers since the early 1980s was observed. The drivers for the observed changes vary geographically. In the western area, the changes are mainly attributed to bottom-up effects of phytoplankton growth and development, while in the eastern areas sea surface temperature is more important.

Introduction
Climate-induced changes in sea surface temperature, phytoplankton biomass and the North Atlantic Oscillation (NAO) have been suggested as causes of several long-term variations or shifts in phytoplankton and copepods in the North Atlantic (Beaugrand and Reid, 2003; Beaugrand *et al.*, 2003; Edwards and Richardson, 2004; Reid and Valdés, 2011), which in turn may affect higher trophic levels by asynchrony between production at the base of the food web and at higher levels. Krill are key species in the North Atlantic, serving as food for many marine animals as several fishes, marine mammals and sea birds. The main purpose of this study was to describe the long-term changes of krill in CPR areas close to Iceland. In particular, we aimed at evaluating the relative contributions of climate variables, as well as the phytoplankton spring bloom timing and biomass on the multidecadal variability of krill.

Materials and Methods
The investigation is based on monthly data of krill abundance collected by the CPR survey in the eastern North Atlantic Ocean (58−66^{0}N, -43^{0}W−3^{0}E) from 1958 to 2007. CPR collects plankton continuously at monthly intervals on standard routes by commercial vessels at a mean depth of ~7 m. Sea surface temperatures, salinity and chlorophyll *a* (Chl *a*) and NAO were used as explanatory variables. Additionally, phytoplankton bloom initiation was estimated from surface Chl *a* concentrations, start of blooming defined as when Chl *a* concentrations increased 5% above the annual median (Siegel *et al.*, 2002). Generalized additive models (GAMs) were used to analyse long-term changes of krill abundance as function of hydrographic and biological variables (Wood, 2006). An approach combining two models – presence/absence (A) and abundance larger than zero (B) – was used. Model A was used to analyze what explanatory variables dictate krill habitat and model B was used to determine the variables that favour an increase in krill abundance.

Results and Discussion

In surface layers the abundance of krill gradually decreased from the east of Greenland to the east of the Faroe Islands, indicating Irminger Sea as a high productive area or population centre of krill in the North Atlantic. From 1958 to 2007 our findings show that krill abundance has declined in CPR areas A6 (r^2=0.25, p<0.001), B7 (r^2=0.11, p<0.05), B5 (r^2=0.22, p<0.001) and B4 (r^2=0.22, p<0.001) while not in area B6. The lowest values in areas B6, B5, and B4 were observed in 2007 (Figure 1).

GAMs indicated that krill habitat was explained by temperature (in area B7 and B4) and Chl *a* concentration (in area A6, B6 and B5). The explanatory variables for the observed changes in krill abundance vary geographically. Phytoplankton bloom initiation (A6), Chl *a* concentration (B7 and B5), and temperature (B6 and B4) were important in describing the abundance of krill. Krill numbers in area A6 tended to be highest when the spring bloom started between weeks 19 and 21, i.e. late May (deviance explained 31.4%). In areas B7, B6 and B5, the highest krill numbers were observed when the surface Chl *a* concentrations were >1.6 mg m^{-3}. The importance of temperature gradually increased from area B7 to B5. The highest numbers were observed when the temperatures in the surface layers were >6.5°C in area B7, >9°C in B6 and >9.5°C in B5.

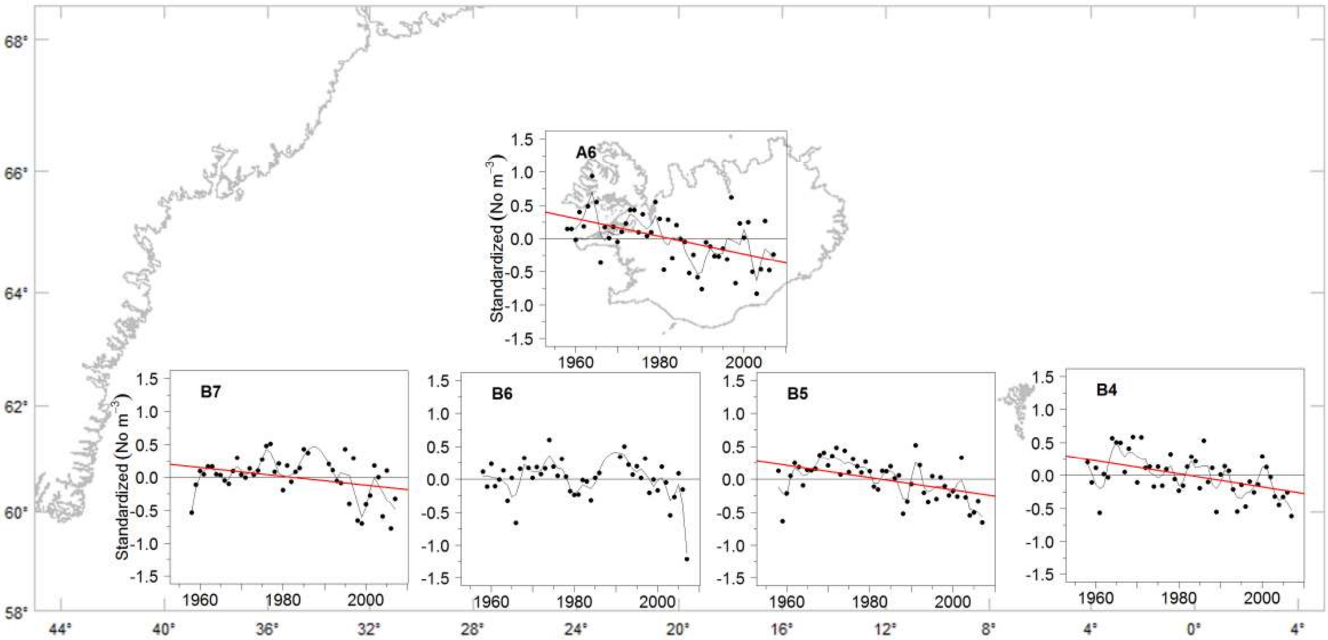

Figure 1. Interannual variation in abundance of total krill in the CPR areas from 1958–2007. Abundances are standardized to zero mean and unit variance. Curved line is a loess smoothed curve with a span of five years. Regression lines significant at p<0.05 level are shown by straight red lines.

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