On the predictive potential of spatially-explicit IBMs: Can larvae fish IBMs be used to predict recruitment success, results from a multi-decadal simulation of Atlantic cod (Gadus morhua) in the North Sea

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Summary
Recruitment of Atlantic cod (*Gadus morhua*) in the North Sea is determined by a chain of processes impacting survival of early life stages, which are difficult to derive from observations only. Here, we utilized a spatially-explicit Individual Based Model for North Sea Atlantic cod linked to a 3d ecosystem model (ECOSMO) to disentangle processes relevant for long-term changes in potential larval survival (PLS). The model was integrated over a 60-year time period (1949-2008) and the results were analysed using common statistical methods. The simulated long-term dynamics in annual PLS exhibited pronounced year-to-year variability and a significant decrease after 1989. Ten environmental parameters were analysed with respect to their relevance for PLS whereof only water temperature and the u-component of the velocity field showed the same significant shift after 1989. A subsequent correlation analysis with observed Atlantic cod recruitment in the North Sea revealed significant changes in correlation during the considered time period indicating general shifts in process interactions relevant for recruitment. Our analysis revealed that the model is able to produce a cod recruitment index with significant predictive capacity during specific time periods and hence.

Introduction
Atlantic cod (Gadhus morhua) is a demersal gadoid that has traditionally been one of the most abundant predatory fish in the North Sea. During the last decades, the abundance of Atlantic cod in the North Sea has markedly declined (Beaugrand *et al.*, 2003). This might potentially be caused by extensive (over-) exploitation of the stock, but several studies also indicate major impacts by changes in the prey field (bottom-up) (Beaugrand *et al.*, 2003), water temperature (Brander and Mohn, 2004) and in the predator fields (top-down) (Kempf *et al.*, 2009).
An appropriate tool for identifying climate implications for fish are spatially explicit Individual Based Models (IBM) since they allow for a number of relevant scenario experiments with relatively minor efforts. Here we show that multidecadal applications of the latter allow not only the identification of process interactions relevant for very early life stages, but can likewise be a tool for understanding recruitment variability.

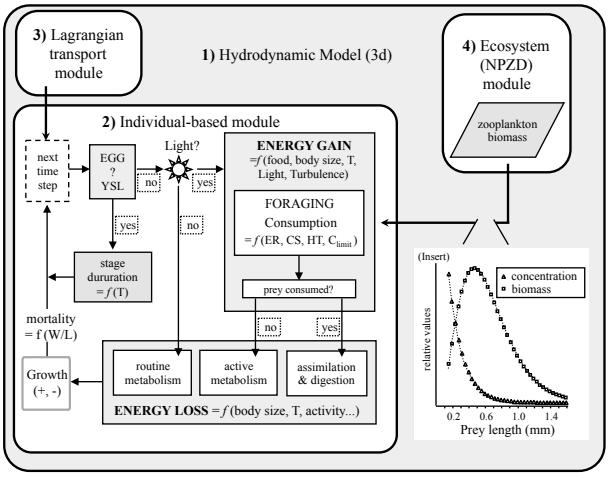

Figure 1: Conceptual diagram of the coupled model structure (from Daewel *et al.,* 2011**). The IBM and a Lagrangian transport module are implemented in the hydrodynamic core. The IBM consists of the egg, yolk-sac and feeding larval stages (*E*: egg, *YS*: yolk-sac, *LS*: larval length, *T*: temperature, *L*: light, turb: turbulence, *ER*: encounter rate, *CS*: capture success, *HT*: handling time, *Cmax*: maximum consumption). The ecosystem model "ECOSMO II" provides zooplankton biomass that is conversed into a size specific prey field (Insert) and utilized by the IBM foraging subroutine.**

Methods
Here we employed a spatially explicit IBM (Daewel *et al.*, 2011; Fig. 1) that base on the 3d bio-physical model ECOSMO II (Schrum *et al.*,

2006; Daewel and Schrum, 2013) for a 60 year time period (1949-2008). The model simulates Atlantic cod early life stages until larvae reach a predefined body length of 20 mm. The IBM is coupled online to the physical model of ECOSMO using a Lagrangian transport model. Prey fields are obtained from complementary run with ECOSMO II.

Results & Discussion

The model produces spatiotemporal variable fields of PLS (%), development time of non-feeding stages (NFS) (days) and larval growth rates (GR) (m day^{-1}). In figure 2 long-term changes and 5yr running means for all three parameters are presented. The filtered time series indicate multi-decadal variability with a clear decrease in PLS and NFS between the end of the 1980ies and increasing growth rates between 1995 and 2000. Statistical analyses concerning impacts of environmental factors highlight particularly the impact of temperature and transport fields for estimated PLS. Comparing the results to recruitment data (available from www.ices.dk; see Olsen *et al.*, 2011), we found that the estimated PLS was significantly correlated to recruitment during some of the periods, but exhibited no correlation during the 1980ies. This allows hypothesising that during some periods Atlantic cod recruitment is strongly linked to the potential survival of early life stages, whereas during the 1980ies other, in the model not resolved, processes such as predation by herring (Speirs *et al.*, 2010) play a more important role and potentially decouple recruitment from 'bottom-up' impacts like temperature and prey availability.

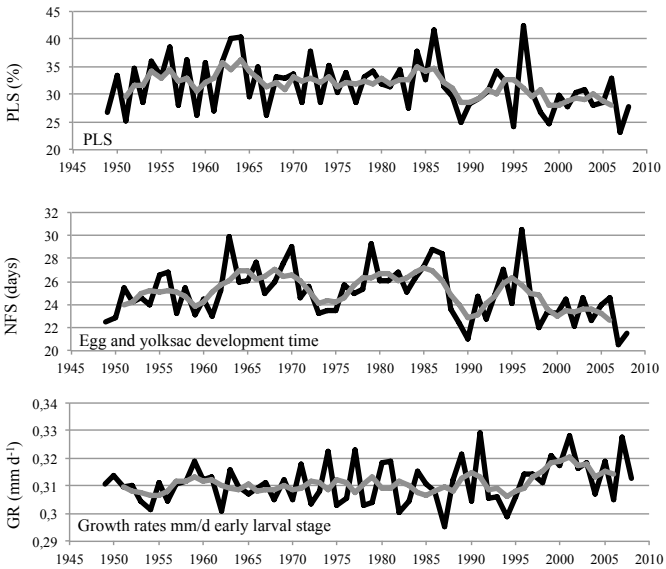

Figure 2: Simulated changes in potential larval survival (PLS; upper), duration of non-feeding stages (NFS; middle), growth rate of feeding larvae < 10mm (GR; lower).

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