CORRESPONDENCE:

Sources of uncertainties in cod distribution models

To the Editor — Wisz *et al.*[1] predicted a substantial exchange of fish species between the Atlantic and Pacific oceans across the Arctic by 2100, including up to 41 species entering the Pacific from the Atlantic. Special attention was given to three commercially important species Atlantic cod (*Gadus morhua*), Atlantic wolffish (*Anarhichas lupus*) and yellowfin sole (*Limanda aspera*). By 2100, they were predicted to colonize the Northeast Passage, potentially providing additional opportunities for high-latitude fisheries.

Central to projections of future fishing opportunities and species diversity in the Arctic are correct predictions of propagation limits of the individual species. According to Wisz *et al.*, Atlantic cod would find suitable environmental conditions in the southern and central Barents Sea by around 2060–2100, concurrently with the Laptev, East-Siberian and Chukchi seas (Fig. 1a). The northern Barents Sea would, according to these simulations, not be suitable even by

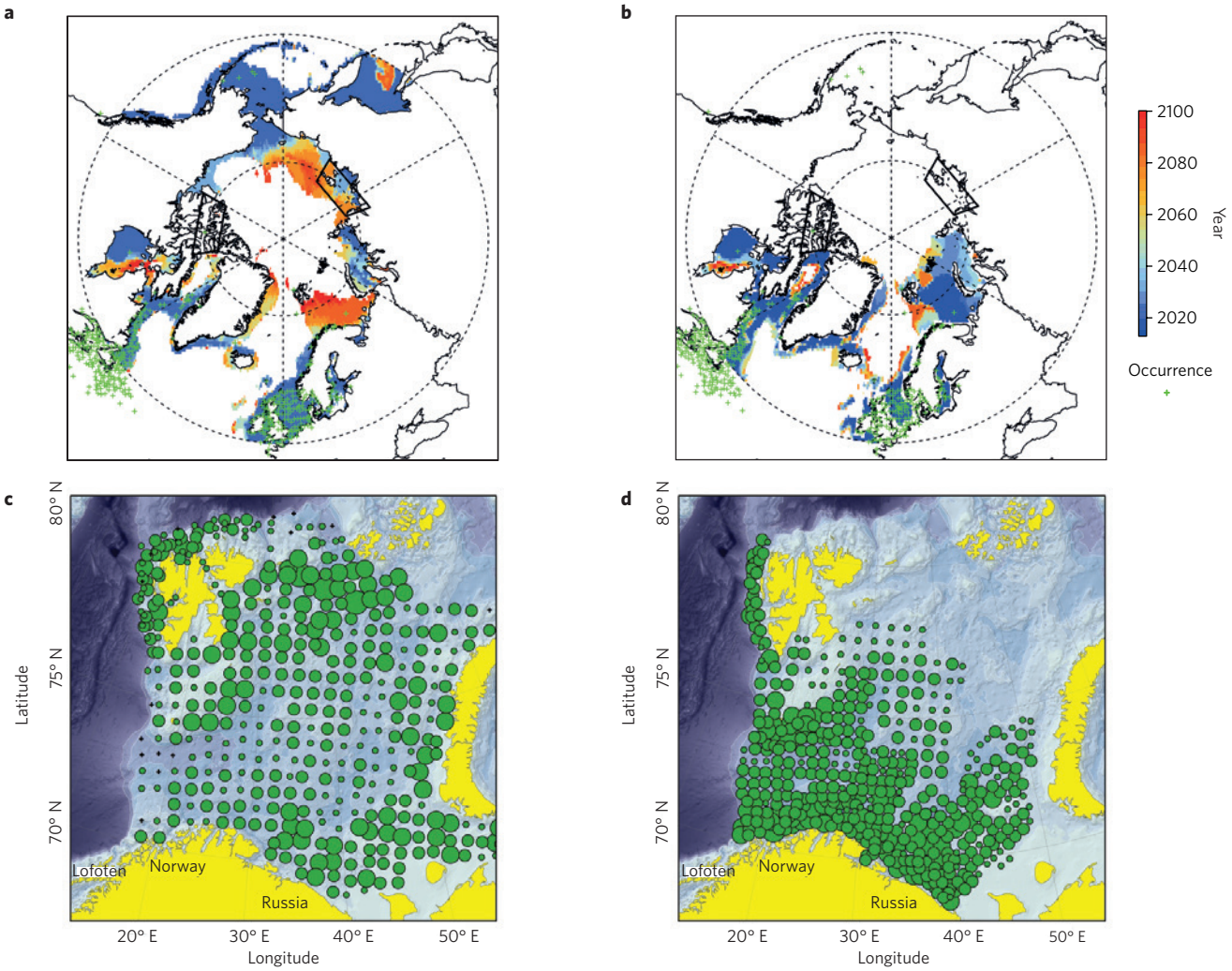

Figure 1 | Projection of suitable environmental conditions for Atlantic cod (*Gadus morhua*) based on niche-models and observed current distribution of Atlantic cod in the Barents Sea. **a**,**b**, Projections of suitable environmental conditions based on the EC-Earth model Representative Concentration Pathway (RCP) 8.5 (**a**) and the IPSLCM5A-LR model RCP 8.5 (**b**) scenarios. Colour scale indicates the forecasted year in which conditions become suitable for cod. **c**,**d**, The catch rate of cod in the Barents Sea in autumn 2013 (**c**) and winter 2014 (**d**). Data from: **c**, ref. 11; **d**, ref. 12. The circle size corresponds to the catch rate (smallest is <100 individuals per nautical mile, largest indicates >5,000 individuals per nautical mile). Panels **a**,**b** reproduced with permission from ref. 1, Nature Publishing Group.

2100. We will explore in our response how the nowcasts and forecasts of Wisz *et al.* correspond to currently realized fish distributions for Atlantic cod.

How do these scenarios compare with the current Barents Sea cod stock distribution? The Barents Sea cod stock is the world's northernmost stock of Atlantic cod with a well-described distribution pattern (see refs 2–4, for example). An example of the distribution during late summer and winter is given in Fig. 1c,d. During late summer, cod are feeding all over the Barents Sea, while during winter, when the northern Barents Sea is ice covered, cod migrate southwards towards the wintering grounds in the southern Barents Sea and the spawning areas along the Norwegian coastline. In recent warm years, the northern border of the cod summer feeding distribution in the Barents Sea has expanded to 80–82° N (Fig. 1c), north of Svalbard and Spitsbergen[5]. This means that cod are already present far north of the areas Wisz *et al.* predicted to become suitable with regard to the environmental conditions by 2060–2100. What could explain such a large discrepancy, which has large ecological and economical implications?

Projection of physical parameters as basis for changes in species. There is a wide spread in the projected climatic changes among global climate models[6]. While the mean of all models is near to historical observations, important biases exist for the simulated sea-ice extent in individual models[7]. Thus, the outcome of a projection including, for example, future sea-ice extent based on a single climate model will be highly sensitive to model selection, as also illustrated by Wisz *et al.* (Fig. 1a,b). For example, their results from a different climate model indicated that the major part of the Barents Sea had suitable environmental conditions for cod today (which fits with observational data — see, for example, ref. 5), while the Laptev, East-Siberian and Chukchi seas would hardly have such conditions even by 2100 (Fig. 1b). Similar differences due to the different climate change scenario selected were evident for Atlantic wolffish. So differences in the climate forcing used for the niche-based modelling do have tremendous effects in model outcomes.

Various approaches have been used to reduce the uncertainty and the sensitivity to choice of climate model. One commonly applied approach (also used by the IPCC[6]) is the use of an ensemble mean of models. Additionally, some studies removed models that cannot simulate the present-day climate (for example, refs 8,9). Similar approaches were not applied when presenting suitable conditions for Atlantic cod in the study by Wisz *et al.* The discrepancy between simulated suitable environmental conditions and the actual currently realized cod distribution can at least partially be explained by their choice of this single climate model. We agree with Wang and Overland[8] that careful evaluation and selection of models with regard to the current physical environment are essential when selecting models for projection studies. We suggest that the use of a robust ensemble of climate models will provide more reliable projections and predictions of future fish distributions in the Arctic.

Current and future fisheries. Cod is an important commercial species, being ranked 11th in 2012 when assessing the world fisheries landings[10]. Of all Atlantic cod stocks, the Barents Sea stock is the largest at present[5] and has provided between 43 and 75% of the total annual catch of Atlantic cod since the mid-1990s (Fig. 2). For example, for 2015, the total allowable catch for cod in the Barents Sea has been set at 894,000 t. In total, 14 nations (mainly Russia and Norway) are fishing on this stock (www.ices.dk). Thus, predictions related to changes in the distribution of this stock have great economical and potentially fisheries management implications. We suggest that a thorough validation of the environmental models to properly match the present situation, both in terms of environment and fish distribution, should be the next step before any further predictions of the future distributions of commercially important species. ❐

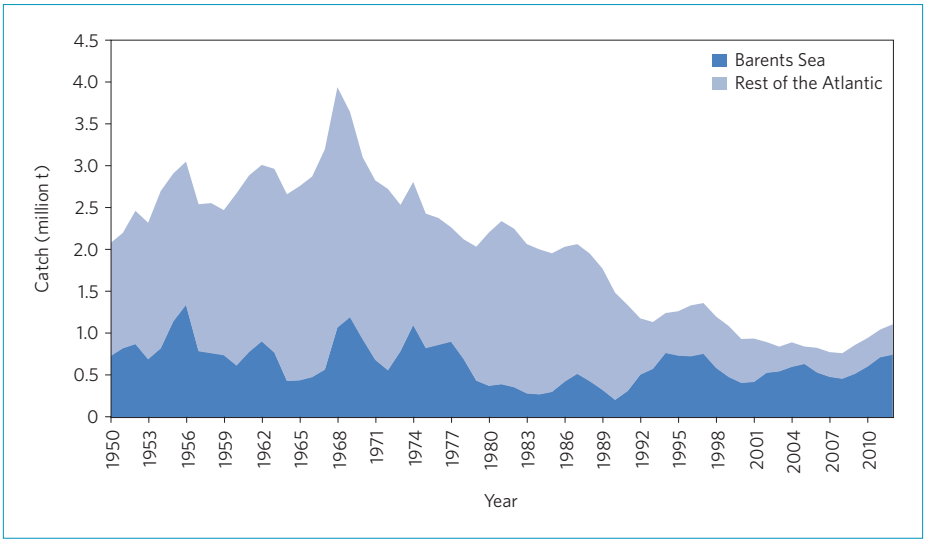

Figure 2 | Catch of Atlantic cod in the Barents Sea and in the rest of the Atlantic. Official catch statistics are available at International Council for the Exploration of the Sea (www.ices.dk) and Food and Agriculture Organization Global Capture Database (FishStat, http://data.fao.org).

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