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Reply

Reply to “Towards a more balanced assessment of the dynamics of North Atlantic ecosystems—a comment on Drinkwater and Kristiansen (2018)”

Drinkwater, K. F. Kristiansen, T. Reply to “Towards a more balanced assessment of the dynamics of North Atlantic ecosystems—a comment on Drinkwater and Kristiansen (2018)”. – ICES Journal of Marine Science, 76: 2495–2499;

We thank Ken Frank and colleagues for their interest in our paper (Drinkwater and Kristiansen, 2018; hereafter D&K) and for their comments (Frank *et al.*, 2019; hereafter FPLB). We agree with them that in investigations of the dynamics of North Atlantic ecosystems both fisheries and climate need be considered to produce a balanced assessment of the mechanisms controlling ecosystem changes. We acknowledge this in the abstract and near the end of the paper, but not in any quantitative manner or with any detailed discussion, which was beyond the scope of the paper. As stated in our paper, our objective was not a detailed study of ecosystem dynamics but rather a more limited objective, i.e. first to document the ecosystem changes that occurred in the northern North Atlantic during a relatively cold period throughout the 1960s and 1970s and second to compare those changes with what happened in the previous and following warmer periods. In this reply we primary deal with the three main issues that FPLB raised. These were: (i) the role of fisheries exploitation on the ecosystem changes in the NE Atlantic, around Iceland, off West Greenland, and off Newfoundland/Labrador; (ii) the assumption that the local temperature climate in these regions can be represented by the Atlantic multidecadal oscillation (AMO); and (iii) the issue of east to west propagation of ocean temperatures as a possible cause of Atlantic cod (*Gadus morhua*) declines during the cold period. We will deal first with issues (ii) and (iii) and then return to issue (i).

AMO

The Atlantic Multidecadal Oscillation (AMO) is a large-scale temperature index based on the annual mean sea surface temperature (SST) averaged over the North Atlantic after the linear trend has been removed and a low-frequency filter applied (Enfield *et al.*, 2001; Sutton and Hodson, 2005). Different authors who have calculated AMO indices report slightly different values depending on the area and filter used, as well as the SST dataset chosen. The averaging generally occurs over an area of the North Atlantic from the equator to 60°, 70°, or 80°N. The filter applied usually has a time-scale of 10 years or more but the filter type varies. The AMO index calculated to 70°N is available online at https://www.esrl.noaa.gov/psd/data/timeseries/AMO/. Regardless of the details of the method used, the AMO indices all exhibit low-frequency temperature variability with a period of ~60 to 80 years (see Sutton and Hodson, 2005) since at least the 1730s (Sænger *et al.*, 2009). A positive AMO index is associated with above average North Atlantic SSTs and a negative index with below average temperatures. The signal is not only limited to the North Atlantic but has also been shown to extend into the Arctic (Chylek *et al.*, 2009; Drinkwater *et al.*, 2014). The AMO accounts for ~60% of the warming in North Atlantic SSTs from 1970 to 2000 (Polyakov *et al.*, 2010).

The AMO index shows generally cool conditions in the late 1800s and early 1900s, relatively warm during the 1930s–1960s, cool in the 1970s and 1980s and has returned to warm conditions since the 1990s (Figure 1 in D&K; see also Sutton and Hodson, 2005; Alexander *et al.*, 2014). However, we acknowledge that temperatures throughout the North Atlantic do vary spatially and temporally (Figure 3 in D&K) and not always in phase with the AMO. Spatially there is a strong horseshoe-shaped pattern of SST anomalies with the highest correlations between the AMO index and local SSTs occurring off southern Greenland, extending towards southern Europe, south along the eastern North Atlantic and then west towards the Caribbean in the tropics (Goldenberg *et al.*, 2001; Deser *et al.*, 2010). Thus, FPLB are correct to question how representative the AMO index is of the regions we investigated in D&K.

FPLB examined temperature time series for stations in the Barents Sea, north of Iceland, off West Greenland and off Newfoundland and Labrador. Based on their correlation analysis, the AMO accounts for 40–60% of the low-frequency variability for the Barents Sea, off Iceland, and off Northern Newfoundland. Not surprisingly, their correlations using annual data are a lot lower but one would not expect a high correlation with a broad-scale index and local temperatures at such a relatively high frequency.

The low-frequency results found by FPLB for the Barents Sea are consistent with those found by Skagseth *et al.* (2008), Levitus *et al.* (2009), and Drinkwater *et al.* (2014). The latter calculated a correlation of 0.83 between the 10-year running means of the AMO and the Kola Section temperatures in the Barents Sea over the years from the 1920s to 2010s, consistent with, but slightly higher than, that found by FPLB (0.77 for the years 1940–2016). As with all correlations with the low-frequency AMO signal and datasets of generally <100 years, the results are not statistically significant as there are few degrees of freedom.

Off West Greenland FPLB found a correlation between the AMO and West Greenland Sea temperatures of 0.39, which accounts for only 15% of the temperature variability. The West Greenland temperature time series they chose was the June–July measurements at station 4 on the Fyllas Bank Section taken from Mortensen (2018). This station lies at the edge of the West Greenland Shelf over the continental slope and is near the front separating shelf waters and the offshore Irminger Current waters. We contend that conclusions based on data from this station must be viewed with caution given their possible temporal (collected mostly once per year and in different months in some years) and possible spatial bias (near a temperature front). Several studies and datasets support this view. Lloyd *et al.* (2011), showed a link between the AMO and West Greenland ocean temperatures in an investigation of changes in the ice margin position of the glacier Jakobshavn Glacier (69.17°N 49.83°W) over the past 100 years. Periods of warm/cold subsurface ocean temperature changes led to glacier retreats/advancements. They also observed benthic foraminiferal data from Disko Bay, adjacent to the Jakobshavn Glacier. The faunal data consisted of representative "warm" and "cold" species that showed warm ocean currents entered the bay during the retreat phases of Jakobshavn Glacier from 1920 to 1950 and since 1998, corresponding to the warm periods of the AMO. In a somewhat analogous study, Vermassen *et al.* (2019) found a relationship between the AMO and warm/cold water in Upernavik Fjord, farther north (72.9°N 55.5°W) on West Greenland. Their results were also based on foraminifera and similar to Lloyd *et al.* (2011), warmer water conditions corresponding to times of glacial retreat. In D&K, we showed that the AMO accounted for slightly >50% of the variability in the sea ice (called "storis") duration off West Greenland between October and the following September for 1899/1900–1971/1972, using data from Valeur (1976) (see Figure 5 in D&K). Drinkwater *et al.* (2014) found a correlation of 0.49 between the AMO index and Nuuk air temperatures, thus accounting for around 25% of the low-frequency air temperature variability. Nuuk lies ∼86 km east-southeast of Station 4. Finally, the highest amplitude of the AMO SST pattern derived by regressing detrended North Atlantic annual mean SST anomalies using the HadISST dataset (Rayner *et al.*, 2003) on the observed AMO index for the period 1870–2015 was found off southern Greenland and extended along southwest and southeast Greenland (Trenberth *et al.*, 2019). These various studies suggest that the AMO may be a better indicator of the low-frequency sea temperature trends off the West Greenland Shelf than that suggested by the Station 4 data. However, further examination of the West Greenland ocean temperatures is warranted. Overall, we conclude that the AMO generally represents ∼25 to 60% of the low-frequency ocean temperature variability in the areas we investigated.

Before leaving this discussion, we must return to the referenced statement in FPLB that because the AMO Index (and hence SSTs) has a very low amplitude, its physiological and population level impacts will be negligible. We agree that the amplitude is indeed small, however, we contend that one needs to consider the time or duration of the signal, not only its amplitude. Thus, it could be, on average, persistently cold for the duration of the life of a cod (say a 5–8 years old) during the cold phase of the AMO and warm for cod living during a warm phase. For an AMO amplitude of only 1°C, the cumulative temperature difference between those at the warm and cold periods of the AMO would be 1°C per year, which over the life of a 5- and 8-year old cod, the cumulative difference would be 5–8°C, certainly not negligible. For example, in a previous study we analysed how warm and cold phases affect overall survival and recruitment of Atlantic larval cod by increasing and decreasing the annual period available for feeding and growth (Kristiansen *et al.*, 2011). Even using the lower amplitude of 0.4°C of the AMO signal as seen in Figure 1 of D&K, the cumulative difference between the warm and cold periods of the AMO would be 2°–3°C over the life of the 5- to 8-year old fish, still not negligible.

Westward propagation of temperature and its relationship with cod declines

In D&K, we noted that the timing of the decline in the cod Spawning Stock Biomass (SSB) in the Barents Sea, off Iceland, on the West Greenland Shelf, and the off Northern Newfoundland and Labrador occurred progressively later the farther west the stock. We also pointed out that Frankcombe *et al.* (2008) found a low-frequency, westward propagation of temperature anomalies across the North Atlantic, primarily at subsurface depths. We continued by asking the question whether climate, as measured through ocean temperatures, could have played a role in the decline and the temporal delay from east to west in the decline. However, our attempt in D&K to match the delay in the SSB declines with the declines in SST using the Simple Ocean Data Assimilation SST database was unsuccessful, except for the timing between the Barents Sea and Northern Newfoundland/Labrador. We concluded that it remains unclear what role temperature may have played in the decline of these four cod stocks and the temporal delay.

FPLB rightly point out that several authors have suggested that the delay in the decline of the cod SSB occurring progressively later to the west was a result of fishing intensity moving westward, especially the mobile fleets such as those from countries such as Russia. We were perhaps amiss not to have mentioned it in our paper. However, we do know that the decline in the cod stocks off West Greenland and Newfoundland did occur during relatively cold periods. We do not conclude that climate explains most of the decline, for if there had been no fishing, these cod stocks would not have declined to the extent that they did. In the West Greenland case, the rise in the cod stocks in the 1920s–1960s certainly cannot be attributed to a reduction in fishing. Danish and German expeditions to the region in the later part of the 19th century were sent to determine if there were commercial concentrations of fish but they could not find any (Buch *et al.*, 1994). In 1909, another scouting expedition did find enough cod for commercial fishing (Jensen, 1949). By the 1930s a commercial fishery for cod was well established and by the middle of the warm period, cod catches off West Greenland reached upwards of

500 thousand metric tonnes. It is believed that the cod initially came from Iceland and once on the West Greenland Shelf, environmental conditions at the time contributed to the increased cod production (Jensen, 1949; Dickson and Brander, 1993). If climate played a role in the increase in the stocks, could it not have also played a role in the decline? Still, intensive fishing is acknowledged as having the major impact in the decline.

In a similar manner, warm conditions in the Barents Sea throughout the 1930s–1950s coincided with the increasing abundance of cod there while the decline occurred during a period of colder temperatures (Blacker, 1957; Drinkwater, 2006, 2009). The effect of temperature on cod in the Barents has been explored by numerous studies, all of which show the smallest abundances occur during cold periods and the highest abundances during warm periods (Ottersen *et al.*, 1994; Godø, 2003; Drinkwater, 2009) although warm temperatures appear to be a necessary but not sufficient condition for high cod stocks, at least historically (Loeng, 1989; Ottersen and Loeng, 2000). Godø (2003) also noted that the substantial long-term variability in the cod stock coincides with similar fluctuations in the environment. Off Newfoundland, intensive fishing indeed resulted in a decline in the cod stocks there, but during the late 1980s and 1990s as the cod stocks declined, the condition of the fish also deteriorated (Drinkwater, 2002). Fisherman called them “skinny cod” suggesting they were not getting enough to eat. This is believed by some to have been a contributing factor in the decline, either through direct mortality or making the fish more susceptible to being caught. Thus, the climate could have played a role in the decline of this cod stock through its effect on the cod’s prey, although not the dominant factor in the decline, which is clearly attributed to fishing intensity.

The role of fisheries

As stated above, we concur with FPLB that fisheries played a major role in the extensive declines of the cod stocks in the northern North Atlantic since at least the 1950s. This was clearly shown for the Newfoundland stocks by Hutchings and Myers (1994), Myers *et al.* (1996), and Rose (2004). Frank *et al.* (2016) analysed 22 cod stocks in the North Atlantic finding synchronous variability that they showed was linked to fishing exploitation. The recent decline in cod stocks in the Gulf of Maine and the North Sea have also been attributed to fishing (Brander, 2018). It is true that if there had been no fishing, it is likely that most of these cod stocks would not have declined, certainly not to the extent that they did. We did acknowledge the importance of fisheries in controlling fish abundance in D&K. However, the fisheries cannot account for the entire decline and it is likely that climate also played a role in the decline of the cod stocks in the North Atlantic.

This is supported by several studies. For example, Link *et al.* (2012) examined fish productivity in 13 northern hemisphere ecosystems including cod in the Barents Sea and off Labrador/Newfoundland using surplus production models. They found that fishing, environment and trophodynamics each contributed to fish production in all ecosystems investigated with the dominant factor being ecosystem dependent. Rose (2004) also used surplus production models for cod off Newfoundland and found that using just fishing or just environment to model cod dynamics from 1505 to 2004 did not mimic historical observations from reconstructed catches, while using the combination of fishing influences and climate he could model the cod dynamics well. He concluded that the dominant controlling factor varied temporally with the cod collapse in the 1960s being caused mainly by overfishing but the large decline in the cod stock in the 1800s during the Little Ice Age was due to lower productivity. Lilly *et al.* (2008) also acknowledged that fishing has played a dominant role in the dynamics of many cod stocks, but variability in climate has also contributed to variability in recruitment, individual growth and natural mortality. Bonanomi *et al.* (2015), using genetic analyses, concluded that the interacting effects of climate change and high fishing pressure resulted in the cod fishery collapse off West Greenland in the early 1970s. Sguotti *et al.* (2019) applied a stochastic cusp model based on catastrophe theory to show that the variability in cod stock abundance are potentially driven by the interaction between fishing intensity and the environment, and consistent with Rose (2004) that the dominant force varies temporally.

As pointed out by FPLB, fishing can produce top-down effects that can result in changes in the lower trophic levels. While true, there is also overwhelming evidence that climate variability can also cause changes in these lower trophic levels as well as marine plants. Several of these lower trophic changes display low-frequency variability that roughly match with the temperature fluctuations, e.g. phytoplankton as measured by chlorophyll-a in the Atlantic was weakly positively correlated with the AMO (Boyce *et al.*, 2010); Gudmundsson (1998) noted the mean phytoplankton productivity on the Icelandic Shelf increased in warm periods and declined during cold periods; using the Continuous Plankton Recorder data from 1948 to 2004, Edwards *et al.* (2013) found a strong link between both phytoplankton and zooplankton variability over the North Atlantic and the AMO; Beaugrand and Kirby (2010) showed climate affects zooplankton in the North Sea and further that they, in turn, affect cod recruitment; climate effects on zooplankton abundance has been shown off West Greenland (Pedersen and Rice, 2002), Iceland (Astthorsson *et al.*, 2007), in the North Sea (Beare *et al.*, 2002), and in the western English Channel (Hawkins *et al.*, 2003); variability of barnacles on the southern shores of England were linked to the AMO (Mieszkowska *et al.*, 2014); and seaweeds on the southwest coast of the UK were related to temperature changes (Cushing and Dickson, 1976).

Concluding remarks

Both FPLB and we acknowledge that fishing and climate affect fish populations and the ecosystems they inhabit. We agree that to provide an improved understanding of ecosystem dynamics we need a balanced approach incorporating both fishing and climate, as well as linking these with trophic dynamics (Link *et al.*, 2012). The dominant factors also change spatially and temporally as well as interact, often in nonlinear ways. However, we believe that papers that focus on just one of these factors can still provide valuable insights and lead to useful testable hypotheses.

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