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North Atlantic Oscillation and fisheries management during global climate change

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Abstract The North Atlantic Oscillation (NAO) is the most important large-scale climatic oscillation affecting the North Atlantic region. The variability introduced by the NAO affects many meteorological parameters, including wind speed and direction, and differences in air temperature and rainfall, particularly during the boreal winter. The NAO is also known to affect the ocean by changing heat content, sea surface temperature, gyre circulation, mixed layer depth, salinity, high-latitude deep water formation, and sea ice cover. Consequently, the NAO has been widely used to analyze the variability of marine ecosystems. Several researchers found that fishery resources were teleconnected with the NAO variability, resulting in a significant relationship between this climatic oscillation and fishery yields. More precisely, the NAO affects the target species abundance, recruitment, catchability, and body condition. These effects can be cumulative over time and act synergistically. In this study, the available information about this topic is reviewed, and the importance of the NAO as a large-scale climatic oscillation in fisheries management is discussed using an ecosystem approach. We also discuss the possible effects of climate change on Atlantic and Mediterranean fisheries if this change were to affect the NAO pattern.

Keywords Large-scale climatic oscillation · North Atlantic region · Northern hemisphere · Global warming · Fisheries · Food security

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Introduction

Climatic oscillations are sets of atmospheric and sea-surface phenomena that affect average weather parameters and other climatic characteristics across vast regions. These oscillations typically display periodic variability and show different phases. Areas that are remote from each other can experience opposite effects during the same phase. When the phase changes, these areas experience shifted but again opposite effects. This phenomenon, called the seesaw effect, has been known since the Viking Age.

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The Vikings observed empirically that when the winters in North Europe were cold and dry, the coasts of Vinland (between the American continent and Greenland) had less ice, and vice versa (Ogilvie et al. 2000). Sir Gilbert Thomas Walker (14 June 1868–4 November 1958) was the first meteorologist to scientifically measure this variability in the climate conditions within the North Atlantic area (Walker 1924), a phenomenon he called the North Atlantic Oscillation (NAO) (Walker 1924; Walker and Bliss 1932). Interestingly, this prominent scientist is most remembered for his contributions to the description of the El Niño phenomenon and the Southern Oscillation Index (SOI), an atmospheric phenomenon linked to El Niño, which are involved in weather disturbances in the tropical Pacific region. The name El Niño (The Child) refers to the baby Jesus, as the Peruvian fishermen knew that around Christmas a warm current used to arrive and end the fishing season. This observation was the first indication of an important link between fisheries and climatic oscillations.

The NAO reflects fluctuations in atmospheric pressure at sea level between the Icelandic Low and the High over the Azores archipelago. The NAO index was defined by Walker and Bliss (1932) as the difference in surface pressure between two ground stations at similar longitudes but different latitudes, specifically, one at high latitude (Akureyri, Iceland) and the other at mid-latitude (Ponta Delgada, Azores). However, the use of instrumental station-based data is currently considered undesirable, and estimation of the index using remote sensing is preferred, as explained below.

The NAO is the most important source of variability in the North Atlantic region, in time scales from intra-seasonal to multi-decadal up to 20–30 years (Visbeck et al. 2001; Frankcombe et al. 2010). It is associated with variation in many meteorological parameters, including wind speed and direction and differences in air temperature and rainfall, particularly during the boreal winter (December–February) or the extended boreal winter, which goes from December to March (Hurrell and Deser 2009) or from November to March (Wang et al. 2017).

According to Walker (1933), the NAO results in two types of winter in Europe. In one type, atmospheric pressure is high near the Azores and southwestern Europe, and low in Iceland, whereas temperatures are high in northwestern Europe; in the other type, all these characteristics are reversed. The NAO values in these two situations are positive and negative, respectively. It is widely known that the positive phase of the NAO produces above-average westerly winds across northern mid-latitudes and a dry climate in the Mediterranean region, whereas the negative phase produces significant precipitation in southern Europe (Fig. 1).

The NAO is also known to affect the ocean through changes in heat content, sea surface temperature (SST), gyre circulation, mixed layer depth, salinity, high-latitude deep water formation, and sea ice cover (Hurrell and Deser 2009). Consequently, it has been widely used to analyze the variability of marine

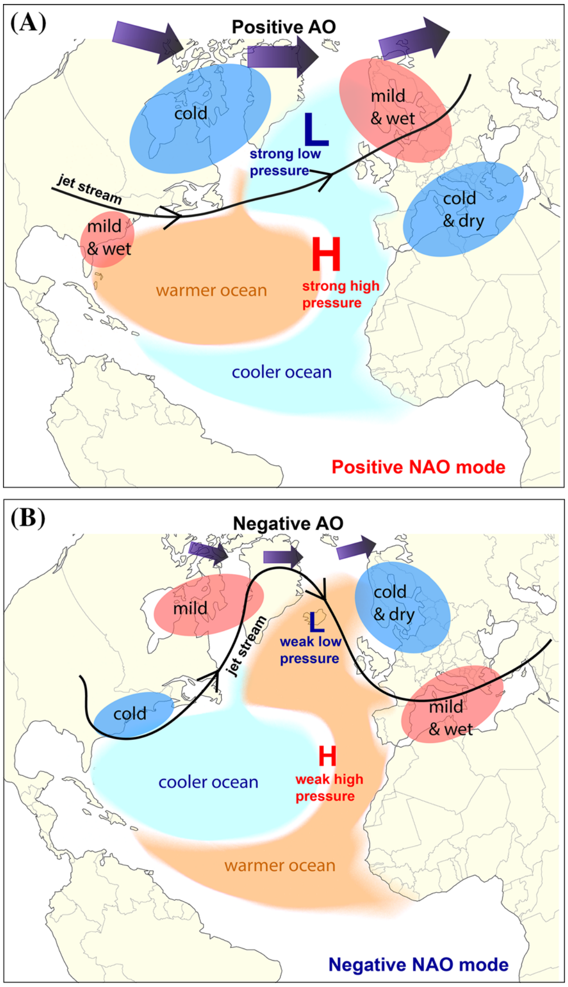

Fig. 1 Schematic view of the positive **a** and negative **b** phases of the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) with their distinctive meteorological and oceanic patterns

ecosystems. Many researchers have suggested that climatic oscillations explain ecological processes, both terrestrial and marine, better than single climate variables. The reason is that climatic oscillations affect multiple weather variables simultaneously, and sometimes in distant areas, in what are called packages of weather (Stenseth et al. 2003) and thus affect the corresponding ecosystem responses (Stenseth et al. 2003; Hallett et al. 2004; Bastos et al. 2016). Such links between ecosystem properties and distant climatic oscillations are called teleconnections (Heffernan et al. 2014). In fact, the NAO index averages meteorological conditions across time and space (Hallett et al. 2004; Straile and Stenseth 2007) and integrates different climate variables in a unique macroscale variable (Stenseth and Mysterud 2005). Some disadvantages of using climate indices are that the patterns and processes they reflect are unclear and difficult to discover (Stenseth et al. 2003; Straile and Stenseth 2007) and that the link between global climatic indices and local climate has yet to be clearly established. Nevertheless, a sometimes underappreciated but critical advantage of using global climate indices is that biological effects may exhibit a longer delay with respect to global indices than with respect to any single local climate variable, making it possible for ecologists to anticipate them and thus make predictions.

According to Ottersen et al. (2001), the clearest influence of the NAO on the ecosystems is through its capacity to affect temperature patterns. For example, positive NAO phases favor major warming during winter-spring, increasing the length of the active growing season for terrestrial plants in north-western Europe (Myneni et al. 1997; Menzel and Fabian 1999). In contrast, negative NAO phases during January favor seed germination and the complex responses of the ecosystem that lead to increased honey production in spring in the Iberian Peninsula, Southern Europe (Báez et al. 2019d). The cumulative effect of the NAO is known to affect the growth and ripening of grapes and the subsequent quality of wines in this area (Real and Báez 2013). In addition, an increase of temperatures driven by the NAO affects the reproductive phenology of amphibians and birds, which spawn or lay eggs earlier in warmer years (reviewed in Ottersen et al. 2001).

Many fishery resources are synchronized with this type of large-scale climatic variability (for example Alheit et al. 2014; Checkley et al. 2017; Faillettaz et al. 2019) and with the NAO in particular (Báez et al. 2019a, b; Tsiklirasa et al. 2019), resulting in an important teleconnection between climatic oscillations and fishery yields. More precisely, climatic oscillations affect the target species abundance, recruitment, catchability, and body condition (Alheit et al. 2014; Báez et al. 2019a, b).

In this paper, we review current perspectives on the NAO. We also provide an overview of the response of fishery resources to the NAO and the specific effects of this climatic oscillation on the biological response and catchability of target species. We review the recent literature and identify the processes involved in the response of fishery resources to this oscillation. Finally, we discuss whether extreme NAO events, alone or in combination with other climatic oscillations, could produce fishery responses that have not been considered in current forecast models and how current climate change may affect these events.

The role of the NAO in the variability of the North Atlantic climate

The NAO reflects the seesaw effect on the redistribution of atmospheric mass between the Arctic and subtropical Atlantic regions; it is linked to North Atlantic weather conditions (surface air temperature, wind direction and speed, storminess, and precipitation) (Visbeck et al. 2001; Hurrell and Deser 2009). When the NAO index is positive, low-pressure anomalies in the Icelandic region and across the Arctic combine with high-pressure anomalies in the subtropical Atlantic to produce stronger-than-average westerly winds at mid-latitudes. In this situation, weather conditions are colder and drier than average over the northwestern Atlantic and Mediterranean regions, whereas they are warmer and wetter than average in northern Europe, the eastern United States, and parts of Scandinavia (Hurrell 1995; Visbeck et al. 2001; Hurrell and Deser 2009). In the Mediterranean Sea, the NAO modifies the water cycle, winds, wind stress and superficial circulation, effects that are more pronounced on the western Mediterranean but are not negligible on the eastern Mediterranean. For instance, the changes associated to precipitation (well documented even in the mountainous regions of the eastern Mediterranean coast, López-Moreno et al. 2011) can have a direct effect on runoff, salinity and SST throughout the Mediterranean. As examples of this, there are several articles documenting the negative correlation of the NAO with SST in the eastern Mediterranean (e.g. Tsimplis and Rixen 2002; Luterbacher et al. 2004; Skliris et al. 2011, Shaltout and Omstedt 2014).

NAO indices

There is no universally accepted NAO index to describe the temporal evolution of the NAO, even if all the available NAO indices represent a normalized air pressure difference between the Icelandic Low and the Azores High (Hurrell 1995; Jianping and Wang 2003; Straile and Stenseth 2007; Hurrell and Deser 2009). The lack of a universally accepted index is due primarily to the tendency to avoid the use of instrumental station-based NAO indices from different meteorological stations (Jones et al. 1997). The main reason is that the center of action of the NAO shifts throughout the seasons and year-on-year (Hurrell and Van Loon 1997), and fixed station instrument values do not reflect well the variable spatial structure of the NAO (Hurrell 1995; Jianping and Wang 2003; Straile and Stenseth 2007; Hurrell and Deser 2009). Consequently, satellite-based NAO indices applied to a geopotential or sea pressure patterns better capture the spatial structure than indices based on subtracting pressure values at two ground stations, as changes in the position of the NAO dipole can affect the centers of action and the two stations are not always representative of the nuclei of the dipoles. This kind of analysis must be done using satellite data or a product such as reanalysis that assimilates satellite data. The lack of periodical and regular instrumental data on the ocean prevented the application of these analysis until the availability of satellites, starting in 1979 (Hurrell and Deser 2009). In addition, the station-based NAO has two other major drawbacks: (1) the existence of noise due to transient and local meteorological events and (2) the lack of homogeneity in the stations pressure series, as the weather stations originally used by Walker and Bliss (1932) were quickly replaced by Reykjavik or Stykkishólmur (high latitude), and Lisbon or Gibraltar (low latitude), with the aim of extending the series back to the mid-19th Century (Cropper et al. 2015).

The NAO index may be calculated from satellite data using two types of methods: linear (e.g., the empirical orthogonal function, EOF) and nonlinear (e.g., cluster analysis) techniques (Barnston and Livezey 1987; Hurrell and Deser 2009). The EOF assumes that preferred atmospheric circulation states come in pairs, with anomalies of opposite polarity having the same spatial structure. By contrast, nonlinear techniques search for recurrent patterns with a specific amplitude and sign and can reveal, for instance, spatial asymmetries between different phases of the NAO (Hurrell and Deser 2009). According to Thompson and Wallace (1998), the EOF better captures the variability of the spatial structure of the NAO, which is probably why it has been most widely used. The EOF is calculated from measurements of the anomalies at a horizontal spatial resolution of 2.5° by 2.5° (latitude and longitude) at an equivalent geopotential height (generally 500 hPa) along the North Atlantic, and a monthly average is extracted from these measurements (Hurrell and Deser 2009). For this reason, the NAO index estimated from the EOF is linear and monthly. Hereafter, unless specifically stated otherwise, we will use "NAO index" to refer to NAO index values estimated from the EOF.

Extreme NAO events

In addition to the sign of the NAO, which determines the direction of storms and the qualitative meteorological conditions and pressure anomalies within the North Atlantic, the quantitative magnitude of the NAO is also important (Durkee et al. 2008). The extremely cold boreal winters of 1996 and 2010, for example, were associated with record negative values of the station-based monthly NAO index (Vicente-Serrano et al. 2011). According to many researchers (for example, Vicente-Serrano et al. 2011), extreme NAO conditions like those observed in 2010 are expected to be more frequent in the future due to climate change (Fig. 2).

Effects of the NAO on fish biology and fisheries

According to Hurrell and Deser (2009), the marine area affected by the NAO extends at least to the subtropical North Atlantic. Consequently, the NAO

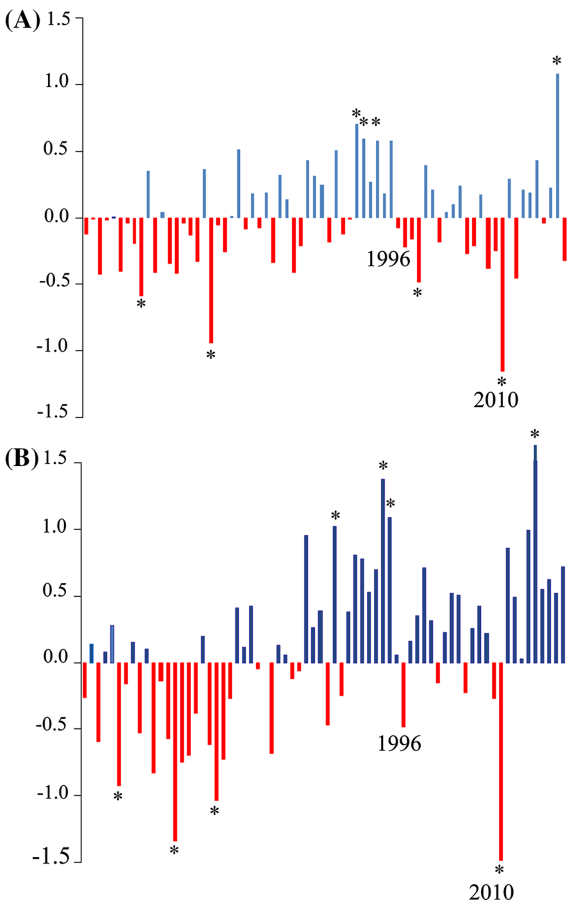

Fig. 2 Annual (**a**) and extended boreal winter (**b**) average time-series of the North Atlantic Oscillation (NAO) since 1951 to 2019. The extreme events are marked and consist of about 10% of the most extreme values observed in the time series, that is, 4 years for the most positive values, and 4 years for the most negative values. Extended boreal winter goes from November to March. The NAO index was obtained from NOAA (https://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml). We also mark the years 2010 and 1996 that are cited in the text

may be expected to affect fisheries in this area. The environmental and oceanographic changes brought about by the NAO may directly affect fish biology or fishing yield, or indirectly lead to an ecological cascade triggered by fundamental changes in ecosystems, such as those affecting primary production (Báez et al. 2014a) (Fig. 3). The ecological characteristics of species that affect fishery activities and yields, and may potentially be affected by the NAO, are the recruitment, abundance, catchability, migration patterns, and fitness (body condition) of the target species. Note that the NAO can affect the same fishing stock biomass in different ways over time (Fig. 3). This effect is cumulative and dynamic (Báez et al. 2011a) and a lag is expected for some effects (for example on recruitment). As the NAO has a seesaw pattern, its effect in positive or negative phase will be opposite and will depend on the area in which the stock is located. For instance, an improvement in the fitness of one stock due to an increase in primary production in the Alboran Sea driven by a negative NAO could have the opposite effect on another stock in the North Sea, and vice versa. Therefore, for different stocks, opposite effects of the NAO wave can be expected depending on their biogeographic context.

Recruitment

Recruitment is the abundance of an annual cohort that enters the harvestable stock for the first time. At the age of recruitment, this cohort is affected by the fishery for the first time. In fisheries management, the level of recruitment is highly variable and is important for establishing population levels (Cadima 2003). Recruitment is affected by mortality during the larval and juvenile periods, which could be affected by patterns of climatic variability (Langley et al. 2009), because fish larvae are sensitive to variations in SST, salinity, acidification, oxygen concentration, and food supply (Gobler et al. 2018; Cominassi et al. 2019). For this reason, many researchers have emphasized the NAO as a driver of the recruitment, abundance and efficacy of many stocks (Mejuto 1999; Borja and Santiago 2002; Báez and Real 2011; Le Bris et al. 2018). A significant and clear example of the effect of the NAO on recruitment, and thus on fishery yields, is the Atlantic cod (*Gadus morhua* Linnaeus, 1758) (Stige et al. 2006; Brander and Mohn 2011; Meng et al. 2016).

The effect of the NAO on recruitment could imply a lag. In short-lived small pelagic fishes (such as sardines and anchovies) the time lag can be very short and effects on successful recruitment are visible in the next year's catch. For example, Teixeira et al. (2016) found a lag of less than a year in the recruitment of the European sardine [*Sardina pilchardus* (Walbaum, 1792)], caused by the effect of the NAO in the previous winter. However, Faillettaz et al. (2019) found a 16-year lagged effect on recruitment in the case of the bluefin tuna [*Thunnus thynnus* (Linnaeus, 1758)]. Thus, for long-lived fishes there is a long lag

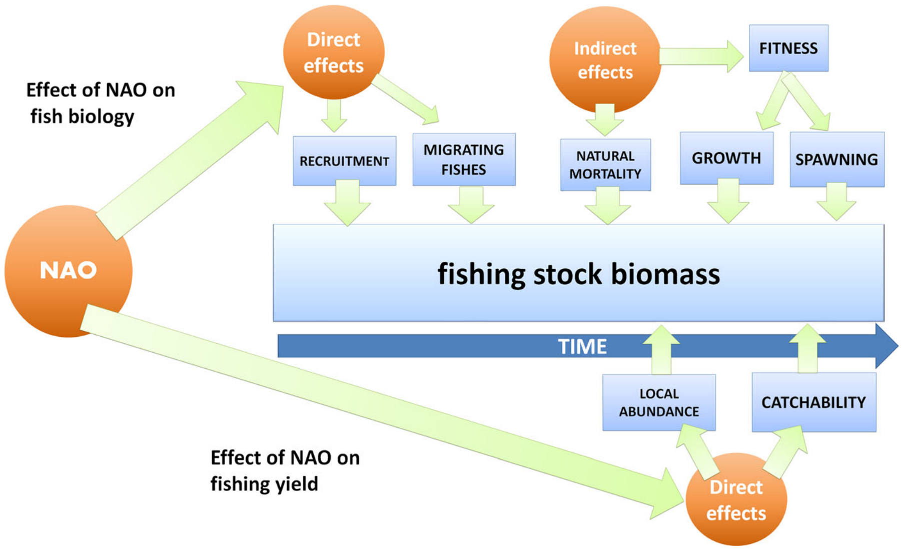

Fig. 3 Conceptual illustration of the different effects of the North Atlantic Oscillation (NAO) on the same fishing stock biomass over time. These effects are cumulative and dynamic. The NAO leads to environmental and oceanographic changes, which in turn could directly affect fish biology or fishing yield, or indirectly lead to an ecological cascade through changes in the ecosystem such as increased or decreased primary production. The timeline ends when the stock interacts with a fishing operation. The order of the effects along the timeline follows the expected order based on its possible lag

between the effect of the NAO on the ecosystem and its possible impact on fishery yields (Borja and Santiago 2002; Goñi and Arrizabalaga 2005).

Local abundance

Owing to rich/poor recruitment driven by the NAO, the abundance of a resource may subsequently increase or decrease (Báez and Real 2011). However, the effect of recruitment on abundance is not always straightforward. Higher abundance of adult bluefin tuna, for example, occurred during both clearly negative and clearly positive NAO phases, whereas lower abundance was observed during periods of intermediate NAO values (Faillettaz et al. 2019). However, the most negative NAO phases had a negative impact on bluefin tuna recruitment, causing a lower abundance 16 years later (Faillettaz et al. 2019). This may explain the contrasting results often found for the effects of the NAO on bluefin tuna recruitment and abundance.

Other studies have indicated a more direct relationship between the NAO and local abundance of small and medium pelagic fish, especially clupeids species (Báez and Real 2011; Auber et al. 2015; Tsiklirasa et al. 2019). This relationship is explained by increases in the availability of food (for example, zooplankton) mediated by the NAO (Fromentin and Planque 1996; Piontkovski et al. 2006). Piontkovski et al. (2006) found NAO-driven interannual changes of zooplankton abundance or biomass in different regions (from the Gulf of Maine to the Aral Sea) in the North Atlantic Ocean basin. A greater availability of food could favor the regional movement of schools of fish and in some way condition the biology of the stocks. Báez et al. (2011a) found that the NAO could have a cumulative effect over the lifespan of fish with moderate longevity, such as albacore [*Thunnus alalunga* (Bonnaterre, 1788)]. In this case, there is a variable lag between the effects of the NAO on the ecosystem and its possible effects on the fishery yield. In other species the lag could be short, as in the case of pre-breeding bluefin tuna of the Strait of Gibraltar (Báez et al. 2013a). The abundance of food could also favor the increase of non-target species and bycatch (Báez et al. 2015). For example, negative NAO phases favor the local abundance of the pelagic stingray [*Pteroplatytrygon violacea* (Bonaparte, 1832)] increasing the bycatch in pelagic longline in the Western Mediterranean Sea (Báez et al. 2015).

In addition, the NAO effects on SST and other oceanographic variables could alter the distribution of species by attracting preys and their predators locally. Faillettaz et al. (2019), for example, found that the NAO was the second or third most important hydroclimatic variable affecting the large-scale distribution of the bluefin tuna in the Atlantic Ocean.

Fishing effort and catchability

Changes in the vertical thermal structure of the ocean associated with the El Niño Southern Oscillation (ENSO) are known to impact the catchability of tuna species by different fishing gears (Bertrand et al. 2020). The thermocline in the western equatorial Pacific is shallower (or deeper) during El Niño (or La Niña) than in neutral conditions (Bertrand et al. 2020). Thus, tuna species, mainly bigeye tuna [*Thunnus obesus* (Lowe, 1839)], could stay out of reach of the purse seiners nets during the La Niña phases. In a similar way, the NAO could alter SST and thermocline. Furthermore, the NAO is associated with storms at sea, which in turn are associated with the catchability of fish, because fishing effort is reduced during stormy days. Thus, the NAO could explain fluctuations in the fisheries harvest via variations in the catchability, which result in changes in the local fishery yield (Rubio et al. 2016). In this case, there is no lag between the effects of the NAO on the ecosystem and its possible impact on fishery benefits.

Therefore, the NAO could have a cumulative effect on fisheries at different levels: recruitment, local abundance, distribution, and catchability (Rubio et al. 2016; Faillettaz et al. 2019; Báez et al. 2020). Báez et al. (2020), for example, found that the NAO affects the dolphinfish [*Coryphaena hippurus* Linnaeus, 1758] catch and bycatch in the Western Mediterranean Sea through different pathways. The impact of the NAO on the fisheries varies depending on the lag in the response of each of these parameters.

Species migration

The NAO affects the migration of many marine animals, for example, bluefin tuna (Gancedo et al. 2009), squid [*Loligo forbesii* Steenstrup, 1856] (Sims et al. 2001), and tope sharks [*Galeorhinus galeus* (Linnaeus, 1758)] (Báez 2016). This implies short lags between the effects of the NAO on the ecosystem and its possible impact on fishery profits (Báez 2016). The NAO alters the migration of many aquatic animals by changing the SST (Svendsen et al. 1995; Ottersen et al. 2001). However, in the case of the loggerhead turtle [*Caretta caretta* (Linnaeus, 1758)], positive NAO phases favor its annual abundance around the Western Mediterranean (Báez et al. 2011b) due to their effect on westerly winds, which secondarily increases its catchability as bycatch in surface longline fisheries targeting swordfish [*Xiphias gladius* Linnaeus, 1758] in the area (Báez et al. 2014b). The NAO also affects post-breeding migration of seabirds, and Paiva et al. (2017) found NAO-driven sexual spatial segregation in Cory's shearwaters [*Calonectris borealis* (Cory, 1881)].

Fitness (body condition)

The body condition of fish generally refers to the fitness of an individual belonging to a specific cohort. Because the weight and length of a fish have an approximately cubic relationship during growth, the body conditions of many fish are easily measurable from the deviation between expected and observed weight. Specifically, this measure is expressed using the Le Cren index (Báez et al. 2013a; Muñoz-Expósito et al. 2017; Báez et al. 2019a, b, c, d). The body condition of top predators is affected by NAO-driven changes in food availability. The energy needs of migratory animals may be reduced if the wind-driven surface currents are favorable during migration during the NAO phase, with the consequent increase in body condition (Báez et al. 2013a, 2019a; Muñoz-Expósito et al. 2017).

Improved physical condition could result in more productive spawning seasons, with spawners laying more and better-quality eggs over a longer period. The better quality of eggs could result in offspring that have higher survival and growth rates, which affect the subsequent recruitment (Berkeley et al. 2004a, b; Birkeland and Dayton 2005). In addition, a longer spawning season could improve the survival rate of larvae (Cushing 1995). In this case, there are short lags between the effects of the NAO on the ecosystem and their possible consequence on fishery profits.

Link between food security and fisheries in the Atlantic region

An estimated 842 million people are chronically hungry (FAO 2014), out of a world population of about 7.7 billion at the end of 2020 (UN 2020). However, in less than 30 years, the Earth's population is expected to reach 9.7 billion people, so there will be a more significant food deficit if current global food production is not enhanced (Báez et al. 2018). Therefore, the greatest challenge facing humanity in coming years is to sustainably increase food production and maintain the improvement over time in the context of climatic variability (Báez et al. 2018; Costello et al. 2020). Seafood plays an important role in addressing this anticipated food deficit (FAO 2014; Báez et al. 2018; Costello et al. 2020).

As explained above, fish stocks exhibit various and cumulative responses to NAO fluctuations. In addition, extreme NAO events are expected to be more frequent in the future owing to climate change. Thus, global warming, through its effects on the NAO, could affect food security in the Atlantic region. Fisheries management policies should be adapted to this climatic situation.

Vulnerability of artisanal fisheries in the Atlantic region to climate change via *the NAO*

The ongoing warming of the oceans at global scale is facilitating the movement of species toward the poles, causing the tropicalization of temperate ecosystems worldwide (Cheung et al. 2013; Báez et al. 2019c). This increase in the abundance of tropical species adapted to temperate areas could accelerate the decline of local habitats, with sharp consequences for the associated ecosystems, and promote changes in the ecological structure of temperate areas (for example, Bellard et al. 2012; Cheung et al. 2013). Therefore, many researchers have predicted a tropicalization of commercial fishing catches due to climate change (Cheung et al. 2013).

Tropicalization has been already observed in the Mediterranean Sea, an area under the influence of the NAO (Báez et al. 2019c), which points to a possible relationship between the NAO and the tropicalization process. Available studies have not obtained any unmistakable evidence of this relationship (Cheung et al. 2013; Pranovi et al. 2013) and more studies are necessary to clarify this matter. The effects of tropicalization due to climate change and mediated by the NAO could be amplified in small-scale fisheries because they are typically located near the shore, highly specialized and more susceptible to changes in the animal community (Pranovi et al. 2013).

Effect of the NAO on industrial fisheries and faux poisson

According to the most recent global fisheries report (FAO 2020), 2018 global finfish production, including fisheries harvest and aquaculture production, was approximately 126 million tons. Approximately 10% of this total production were clupeid fish (i.e. anchovy [*Engraulis ringens* Jenyns, 1842], Atlantic herring [*Clupea harengus* Linnaeus, 1758], European pilchard [*S. pilchardus*], Japanese anchovy [*Engraulis japonicus* Temminck & Schlegel, 1846], *Sardinella* spp.) which, as indicated above, are short-lived and highly susceptible to climatic oscillations. In fact, the FAO report recognizes the effect of El Niño on the increase in the production of anchovy (*E. ringens*). These small pelagic fish are cheap and represent an important source of protein for humans, even if a third of global marine landings is not used for direct human consumption (Zeller and Pauly 2019), but rather used for fishmeal or animal feed, including feedlot-type aquaculture operations that produce carnivorous fish (e.g., Atlantic salmon [*Salmo salar* Linnaeus, 1758]) for developed-world consumers.

Nevertheless, the most important low-cost, non-canned fish for consumption in Africa, usually called with the French term *faux poisson*, includes mainly *Auxis* spp. and fish unsuitable for the international markets, which are known to be affected by NAO fluctuations (Muñoz-Expósito et al. 2017). The *faux poisson* is the main source (and in some cases the only one) of animal protein in Africa (Amandè et al. 2017a,b; Ayilu et al. 2016; Báez et al. 2018). The average landing in Africa over the last 5 years available (2014–2018) (Data source: www.iccat.org from Atlantic Ocean, and www.iotc.org from Indian Ocean) of the two main species targeted by the tropical tuna fisheries, namely yellowfin tuna [*Thunnus albacares* (Bonnaterre, 1788)] and skipjack [*Katsuwonus pelamis* (Linnaeus, 1758)], was 417,000 t and 481,000 t, respectively, in the Indian Ocean, and 132,000 t and 260,000 t, respectively, in the Atlantic Ocean, mostly captured by industrial purse seiners. The average landing of *Auxis* spp. from both oceans was about 200,000 t and was landed mostly in Africa. This amounts, in a conservative estimation, to more than 200,000 t per year of low-priced animal protein usually accessible to the African market that may be compromised by NAO effects. Most *faux poisson* is smoke-dried and transported to be sold in many markets in the interior of Cote d'Ivoire or other countries in the Sahel (Ayilu et al. 2016). A disruption in its trade could undermine the health of those communities that depend on it. This case is another example of how global warming could affect food security in the Atlantic region through the NAO.

Effect of the NAO on fisheries economy

Fishing is primarily an economic activity; therefore, some researchers have suggested the integration of economic drivers of change into ecological–economic models to forecast the effects of climate change (Quaas et al. 2015). Although in principle this may be advisable, climatic variability can also affect economic performance by driving changes in catch prices due to the effects of the NAO on catchability (Fernández et al. 2020). Oremus (2019) obtained positive correlation between NAO and employment in the extraction industry of New England. Thereby, weather variability driven by the NAO could directly reduce marine-related employment due to these effects (Oremus 2019). The NAO affects local wind patterns, and less favorable weather conditions due to the NAO reduce the possibility of going out to fish, as boat skippers could decide, given the weather forecasts, to leave the ships in port, which in turn leads to less economic activity and generates loss of jobs.

One atmosphere, different climatic oscillations

The NAO is not the only atmospheric oscillation that affects climatic patterns in the subtropical North Atlantic region. Other important large-scale climate patterns (in alphabetical order) are the Antarctic Oscillation (AAO); Arctic Oscillation (AO); Atlantic Meridional Overturning Circulation (MOC), Atlantic Multidecadal Oscillation (AMO), East Atlantic (EA) pattern; East Atlantic/Western Russia pattern; ENSO; East Pacific pattern; North Pacific Oscillation; Pacific Decadal Oscillation; Pacific–North American pattern; Pacific–South American pattern; Southern Annular mode (the AAO, but with opposite sign), Scandinavian pattern; Southern Oscillation Index-SOI-; Tropical/Northern Hemisphere pattern; and West Pacific pattern (see Stenseth et al. 2003, for a review). However, these large-scale climate patterns are different responses of the same atmosphere, which may have very distant reflections. Some of these long-distance climate patterns are correlated with the NAO, or even have combined effects. For example, many researchers have highlighted the correlation between the SOI (and El Niño/La Niña events) with the NAO and meteorological conditions in Europe (Rogers 1984; Vicente-Serrano 2005).

The AMO, first proposed by Kerr (2000), is a long-term North Atlantic SST anomaly between Greenland and the equator that responds quickly to the atmospheric-ocean interaction. The AMO and Atlantic SST co-vary with the strength of the MOC. Thus, a positive value (anomalously warm Atlantic) of the AMO corresponds to stronger overturning and a negative value (anomalously cool Atlantic) to a weaker MOC (Frajka-Williams et al. 2017). It causes an ongoing series of long-duration changes in the SST of the North Atlantic Ocean, with cool and warm phases that may last for 20–40 years (Kerr 2000; Enfield et al. 2001; NOAA 2005b). According to Enfield et al. (2001), AMO warm phases occurred in 1860–1880 and 1940–1960, and cool phases occurred in 1905–1925 and 1970–1990. Since the mid-1990s, the AMO has been in a warm phase (NOAA 2005b). The AMO affects air temperatures and rainfall over much of the Northern Hemisphere (Knight et al. 2006). It is associated with the frequency of North American droughts and of severe Atlantic hurricanes. It alternately obscures and exaggerates the global increase in temperature due to human-induced global warming (Enfield et al. 2001; NOAA 2005b). The nature and origin of the AMO are uncertain. Studies of corals, tree rings, estuarine fossil pigments, and sea-spray in Greenland ice cores indicate that a 60- to 100-year oscillation occurred in the North Atlantic region in the centuries preceding the instrumentally observed AMO (Knudsen et al. 2011). However, the available evidence for a pre-industrial AMO remains inconclusive (Knudsen et al. 2011). Alheit et al. (2014) found that the AMO modulates the dynamics of small pelagic fishes and ecosystem regime shifts in the eastern North and Central Atlantic. Faillettaz et al. (2019) showed that the AMO is an important determinant of the spatial distribution and regional abundance of the bluefin tuna in the North Atlantic. The NAO and the AMO interact; from the mid-1960s to the mid-1990s (i.e., in the warm phase of the AMO), the winter NAO index increased from very negative to very positive values (Hurrell and Deser 2009).

Thus, the NAO may be involved in regional ocean–atmosphere interactions with complex regional effects (Marshall et al. 2001), similar to the more complex and larger-scale ENSO-SOI-El Niño interaction in the Pacific Ocean, which has planet-wide effects (Aceituno 1992). The relationship between the NAO and the AO is particularly relevant. Since the AO was first proposed, its physical reality apart from its connection with the NAO has been debated (Christiansen 2007; Báez et al. 2013b). The AO is estimated from the pressure anomalies in the Arctic region and is characterized by a meridional dipole in the sea-level atmospheric pressure between the polar regions and mid-latitudes (Thompson and Wallace 1998). Thus, the AO might more appropriately be thought of as an annular (zonally symmetric) hemispheric mode of variability characterized by a seesaw effect on the atmospheric mass between the polar cap and the mid-latitudes in both the Atlantic and Pacific Ocean basins. Baldwin and Dunkerton (2001) suggested that the signal propagates from the stratosphere downward to the surface; thus, recent trends in the tropospheric circulation over the North Atlantic could be related to processes that affect the strength of the stratospheric polar vortex.

There is currently no consensus on the links between the NAO and AO (Christiansen 2007; Ambaum et al. 2001, Baldwin et al. 2001, 2007; Douville 2009). Competition between two hypotheses remains unresolved: (1) the NAO and the AO are reflections in the troposphere of a common stratospheric cause or (2) they are different phenomena with independent and complementary effects. In any case, although these climatic indices are estimated using different methods, they are highly correlated with r(Pearson) = 0.8 for the mean annual variation and r(Pearson) = 0.9 for the monthly and seasonal anomalies (Deser 2000; Hurrell et al. 2003).

Báez et al. (2013b) performed statistical analyses on the effects of the NAO and AO on SST in the Alboran Sea, both separately and in combination, and found that NAO and AO had synergistic effects when the NAO was negative and the AO was positive. The effects of the NAO and AO alone on SST obscured each other owing to the positive correlation between them. A combined seasonal NAO and AO model explained the SST variability in the Alboran Sea (Báez et al. 2013b), which in turn was found to affect ecosystem responses such as the incidence of jellyfish swarms along the coasts (Bellido et al. 2020) and the fishery of blackspot seabreams [*Pagellus bogaraveo* (Brünnich, 1768)] in the Strait of Gibraltar (Báez et al. 2014c). Báez et al. (2019b) also observed that positive AO phases were related with major capture-per-unit-effort of the sardine (*S. pilchardus*) off northwest Africa in the period 1976–1996.

The EA is the second most important mode of low-frequency variability in the North Atlantic region after the NAO (Barnston and Livezey 1987). The effects of the EA, whose pattern is structurally similar to that of the NAO, are detected throughout the year. The EA pattern consists of a north–south pressure dipole affecting the North Atlantic and spans from east to west with centers between 55° N, 20–35° W and 25–35° N, 0–10° W (Barnston and Livezey 1987). This pattern significantly affects the temperature, precipitation, and wind over western and central Europe (Hurrell 1995; Wulff et al. 2017). The positive phase of the EA is associated with above-average temperatures in Europe and below-average temperatures in the southern United States from January to May and in the northern United States from July to October. In addition, it is also associated with increased precipitation in northern Europe and a corresponding decrease in rainfall across southern Europe (NOAA 2005a). According to Comas-Bru and McDermott (2013), the combined effect of the NAO and the EA more efficiently explains the climate variability on the European continent than the effect of the NAO alone. The reason may be that the EA modulates the strength and location of the NAO dipole (Comas-Bru and McDermott 2013).

The small-scale atmospheric oscillation called the Western Mediterranean Oscillation (WeMO) have been established only over the western Mediterranean basin. According to Martin-Vide and Lopez-Bustins (2006), the WeMO is defined as the difference in pressure between the Po plain (at the Padua station), in the northern part of the Italian peninsula (an area with relatively high barometric variability due to the differentiated influence of the Central European anticyclone and the depression over the Ligurian Sea), and the Gulf of Cádiz (at the San Fernando station), in the southwestern part of the Iberian Peninsula, which is often affected by the Azores anticyclone and, episodically, by the detachment of circumpolar lows or its own cyclogenesis. The main reason for proposing the WeMO is the non-correlation between rainfall in eastern Iberian Peninsula and the instrumental station-based NAO (Martin-Vide and Lopez-Bustins 2006). Long-term climate variability is known to influence fisheries production at various spatiotemporal scales. The WeMO explained the sardine (*S. pilchardus*) and European anchovy (*E. encrasicolus*) variability in the northwestern Mediterranean better than the NAO (Martin et al. 2012).

Implications for fisheries management

When a stock is considered overfished it is necessary to adopt a harvest control rule in the fishery. Two different management controls, or a combination of both, have been mainly performed in fishery: an input-based control, i.e. limits on the total intensity of use of the fishing gear (effort control), and an output-based control, i.e. using a total allowable catch (TAC) (Pope 2002; Sharma and Herrera 2019). The TAC is the most used management measure (Pope 2002; Sharma and Herrera 2019), but it has some disadvantages: it is not usually adjusted annually and often also allows the allocation of the resource between user groups (so the TAC ends up being captured in its entirety even in years with low-abundance stock), and some vessels may misreport their catches (Pope 2002). Some examples of the input-base control are Mozambique deep-water shrimp fishery or purse seine fishery targeting tropical tuna in the Inter-American-Tropical-Tuna area (Pope 2002; Sharma and Herrera 2019). A small-scale example is the near-shore artisanal fisheries from Spain, which abstain from fishing on weekends, being a type of time-at-sea restrictions (Pope 2002).

The inter-annual climate variability due to the NAO could have important implications for fisheries management and marine policy. Input-based control should be preferred over TAC during unfavorable NAO phases. For example, owing to NAO-related fluctuations, a short-lived pelagic fish subject to control by catch quotas per vessel and year could have favorable years with excellent recruitment and unfavorable years with poor recruitment. Regardless of the abundance of the stock and the recruitment level, fishers will always try to reach the maximum allowed quota, which may have disproportionally detrimental effects in unfavorable years. However, effort-based control, such as a maximum number of fishing days, better adjusts captures to the relative abundance in a specific year. In favorable NAO years, when recruitment has been excellent, the increase of yield per set could benefit the fishermen, while in unfavorable seasons captures would naturally be lower. For large, slow-growing fish (such as tunas), unfavorable NAO years entail poorer fitness and lead to worse spawning and lower recruitment. If there is a fixed TAC the consequent fishing mortality could worsen the situation, whereas in fisheries under an input-based control seasonal closures could be ordered. Consequently, fisheries control based on the fishing effort may be more appropriate in a changing world if these changes are appropriately monitored.

Gaps, misinterpretation of the NAO in ecological models, and future studies

The ecosystem approach for fisheries management is a widely accepted concept (Morishita 2008) and typically includes: bycatch mitigation, multi-species management, protection of vulnerable ecosystems, and integrated approaches. The NAO could affect the bycatch, by increasing or decreasing the local abundance of certain non-target species. Integrated approaches must also contemplate the NAO, because it shapes interspecific relationships of potential competitors, for example within the sardine-anchovy complex (Tsiklirasa et al. 2019, and references therein) and prey-predator relationships (Stenseth et al. 2002, and references therein), in addition to the indirect effect it may have on ecosystem structure and fisheries. However, the NAO has rarely been used in ecosystem approach-based fisheries management. The winter index of the NAO and the water temperature have been used, for instance, in forecasts of sprat [*Sprattus sprattus* (Linnaeus, 1758)] recruitment, but they are no longer used due to problems with matching environmental time-series updates with the time of the assessment meetings (MacKenzie and Köster 2004, ICES 2006).

Here it is important to emphasize that not only the NAO, but also the various manifestations of the atmosphere–ocean relationship that can be easily measured using long-scale climatic oscillations, could better explain the fluctuations of fishing resources than local environmental variables. For this reason, and given the unpredictable effects of global warming in coming decades, from an ecosystem perspective, it is necessary to integrate these climatic indices into fishing models and use them in stock assessments (Rykaczewski and Checkley 2008; McClatchie 2014). However, only few assessments explicitly incorporated environmental factors (Rykaczewski and Checkley 2008; McClatchie 2014; Schirripa et al. 2009; Wang et al. 2018). Rykaczewski and Checkley (2008) showed that the increase in the level of wind-stress curl and SST affected the production of Pacific sardine [*Sardinops sagax* (Jenyns, 1842)]. They also showed that the wind-stress curl oscillated over the past six decades and that it is positively correlated with the extent of isopycnal shoaling, nutricline depth, and chlorophyll concentration. In this line, Rykaczewski and Checkley (2008) performed an environmentally dependent surplus production model (EDSP), modifying the Fox surplus production model so that the carrying capacity of the population varies annually as a function of environmental conditions. Other examples of EDSP models have been performed in neon flying squid [*Ommastrephes bartramii* (Lesueur, 1821)] and Argentine shortfin squid [*Illex argentinus* (Castellanos, 1960)] with robust predictions (Wang et al. 2011 2018).

A frequent source of confusion in the application of this type of study is to compare results using different NAO indices, which may differ in their effects and interpretations. For example, Gutiérrez-Estrada et al. (2020) used the station-based NAO between Iceland and Lisbon to compare the results of another study that used an EOF-based NAO (Báez et al. 2014c). Another source of misinterpretation is the difficulty in distinguishing the effects of climate change and climatic oscillations. Marine biodiversity and the fisheries ecology are affected by global warming. Thus, there is increasing concern about the impact of global warming on ecosystems and on the services they provide (i.e., food security). Therefore, many researchers have attempted to forecast the long-term effects of global warming on exploited fish stocks (for example Lehodey et al. 2010, 2013; Dell et al. 2015). Erauskin-Extramiana et al. (2019), for instance, concluded that changes in the distribution of stock biomass are driven by climate change and not by climatic oscillations such as the NAO. However, these studies have been affected by several sources of uncertainty associated with the different atmosphere–ocean general circulation models and emission scenarios provided by the Intergovernmental Panel on Climate Change. These studies have forecast fluctuations in biomass and changes in the distributions of the species under study, but the impact of these effects is difficult to predict owing to the inherent uncertainty of these models and the lack of knowledge about the biological response of species in the short term.

The NAO is an intrinsic mode of variability of the large-scale atmospheric circulation (Deser et al. 2017), its time series can be quite well characterized as a stochastic process (Deser et al. 2010) and its fluctuation at interannual and longer time scale do not need not have an external forcing (Deser and Phillips 2009). However, the NAO can be affected by changes in the conditions due to global warming, such as anomalies of sea surface temperature, anomalous atmospheric circulation in the stratosphere or direct changes in radiative conditions associated with increased concentrations of greenhouse gases (Deser et al. 2012). According to Vicente-Serrano et al. (2011) one predicted effect of climate change is to increase the frequency and magnitude of extreme values of the NAO.

Two decades ago, there was a strong debate about the relationship between the strong positive phase of the NAO from the mid-1960s to mid-1990s and climate change. Some studies suggested that the NAO positive trend was due to a positive SST trend over the Indian Ocean caused by global warming (e.g. Hoerling et al. 2001), while other studies with observations and model simulations maintained that this positive NAO was due only to internal atmosphere–ocean variability (e.g. Raible et al. 2005). If the first hypothesis is true, it is difficult to attribute the effects to these two possible forcing sources, as both have the same direction. In this case, the best choice is the use of climate models run with and without measured greenhouse gases, which allows us to better estimate how much of the common signal is due to the NAO and how much to climate change. However, this problem is not affecting recent analyses due to the current long-term negative phase of the NAO.

The internal variability of the NAO also results in uncertainty in the expected changes in regional climate in coming decades (Deser et al. 2017). The relationship between climatic oscillation indices and local weather, and therefore the corresponding ecological responses, may vary with time; this behavior is known as non-stationarity (Hamilton 1994). There is little evidence for truly stationary periodic behavior in the atmosphere. For example, the SST in the Barents Sea was strongly linked to the NAO early in the twentieth century and from 1970 onward, but the connection was weak between these time periods (Ottersen et al. 2001; Straile and Stenseth 2007).

In a recent study, Alheit et al. (2019) observed a change in the NE Atlantic (and the Mediterranean) marine ecosystems around the mid-1990s, a change concurrent with the shift towards an intense negative NAO phase, finding that the strong correlations between oceanographic or ecological variables and the NAO disappeared or even shifted in sign. There is no doubt that the NAO shifted its phase in the mid-90s. This is something well documented and not unusual in the decadal variability of the NAO (see Fig. 2 in the review by Pinto and Raible 2012). So, along the instrumental period the NAO has changed from a positive phase in the 1910s to a negative one from 1920 until 1960, when it experienced the very well documented shift to a strong positive phase until the mid-1990s. From this moment on, a new negative trend has been observed in the NAO indices. The possible factors invoked to explain this last shift are diverse, ranging from changes in the snow cover to changes in the stratospheric vortex, including also changes in the tropical atmospheric circulation (Cohen and Barlow 2005). However, the most plausible hypothesis seems to be that this shift was due to changes in the dynamical atmospheric processes (Jung et al. 2011). An analysis of the amplitude of the last decadal oscillation (positive phase from mid-1960s to mid-1990s and negative since then) shows stronger decadal variations for the positive than for the negative phase. This could be of importance in the coupling of the NAO with oceans and in the interpretation of Alheit et al. (2019) results. Raible et al. (2011) showed that during phases with enhanced decadal variability the connection between the NAO and the underlying North Atlantic Ocean is much higher than in periods with low decadal variability, when the coupling with the Indian and the Pacific Ocean are higher. So, the effect of the NAO in the positive phase from the mid-1960s to the mid-90s on the Atlantic Ocean and the Mediterranean via surface fluxes of heat, freshwater and momentum should be greater than for the negative phase starting in the mid-90s. An additional reason for this change in the NAO influence since the mid-90s could be the combined effect with the signal of climate change. This last signal is always in the same rising direction, so NAO and climate change could have had additive effects on the ecosystems from the mid-1960 to the mid-90s but competing effects since then.

In summary, the Earth is experiencing a period of rapid global warming, and an expected effect of this climate change is the increased development of extreme climatic oscillations. Extreme phases of short-term climatic oscillations, such as the NAO, can produce rapid and extreme local weather responses, including floods and droughts, and extreme temperatures in the form of heat and cold waves, which affect marine ecosystems and fishery yields, and which should be incorporated into fishery management. Input-based control measured should be preferred in these highly variable and unpredictable expected situations.

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