Getting to know the winter North Atlantic Oscillation

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Abstract: The North Atlantic Oscillation (NAO) is a key atmospheric phenomenon that shapes winter climate patterns in the Northern Hemisphere, affecting sea level pressure, temperature, and precipitation. This study explores the NAO using ERA5 reanalysis data, and coupled atmosphere-ocean and atmosphere-only simulations to analyse its dynamics and impacts. Empirical Orthogonal Function analysis identifies the NAO as the dominant mode of variability, explaining up to 50% of sea level pressure variations in the North Atlantic-European region during boreal winter. Results illustrate that the NAO is primarily an atmospheric phenomenon, independent of oceanic coupling, as evidenced by consistent patterns across datasets. The study highlights the crucial role of the NAO in modulating regional precipitation and temperature patterns, with significant implications for climate research and socio-economic sectors.
Keywords: Geophysics, fluid dynamics, climate, atmospheric processes
SDGs: This work is related to SDGs 6,7,11,13,14,15 (see page 6)

I. INTRODUCTION

The North Atlantic Oscillation (NAO) is the result of the interaction between the Azores High and the Icelandic Low, whose atmospheric masses cause changes in sea level pressure (SLP), sea surface temperature (SST), surface air temperature (SAT), and precipitation patterns. This phenomenon is one of the most studied meteorological and climatic phenomena due to the fact that it is the most recurrent pattern of atmospheric variability over middle and high latitudes in the Northern Hemisphere (NH), particularly from the Arctic to the subtropical Atlantic. It is especially relevant during boreal winter (December, January and February; DJF) [1]. This oscillation, has two different phases: positive (NAO^+) and negative (NAO^-). Changes in the NAO not only cause fluctuations in SLP but also in the meridional oceanic and atmospheric temperature gradient. The strong temperature gradient over the western North Atlantic causes baroclinicity and transient eddies. This latter term refers to the synoptic-scale waves linked to extratropical cyclones that propagate or fluctuate in intensity. The propagation paths are associated with the phases of the NAO: during the positive phase, cyclones follow a meridional path so that precipitation is concentrated over northern Europe; during the negative phase, cyclones follow a zonal (west to east) path towards the Mediterranean, in which case precipitation is concentrated over southern Europe. NAO^+ is related to the fact that the Azores High is stronger than usual and the Icelandic Low deeper, as a consequence high pressure anomalies are present at middle latitudes and low pressure anomalies are present at subpolar latitudes. In contrast, during NAO^- these two phenomena are weaker than usual, so that there are low pressure anomalies at mid-latitudes and high pressure anomalies at subpolar latitudes. Another interesting effect of the NAO is its ability to connect local climate events with global-scale atmospheric processes, which makes it an essential object of study for understanding both short-term climate variability and the potential effects of climate change [2]. In relation to this effect, “a consequence of the atmospheric planetary-scale waves is that climate anomalies on seasonal time scales typically occur over large geographic regions. [...] These simultaneous variations in climate over distant parts of the globe are commonly referred to as ‘teleconnections’ in the meteorological literature” [1]. Because fluctuations in the NAO influence SLP, SST, SAT, displacement of air masses and therefore the formation of cyclones and anticyclones in different parts of the NH, it is considered as a teleconnection pattern and its study is essential for various socio-economic sectors such as navigation, study and prevention of precipitation and droughts, studies on Arctic sea ice fluctuations, agriculture, marine and terrestrial ecosystems, water management and urban planning etc. Yet, our focus is on the regional characterization of the NAO.

In this work the NAO will be studied with different datasets. The first one is the ERA5 reanalysis, which represents observed conditions over 1948-2023. The second dataset is a simulation that takes into account coupled, ocean-atmosphere processes (COUPLED), while the third one is a simulation that only takes into account processes internal to the atmosphere (ATM-ONLY). The comparison between COUPLED and ATM-ONLY allows assessing the role of ocean coupling, namely ocean-atmosphere interaction, on the NAO-related variability [3].

II. METHODOLOGY AND DATA

As mentioned above, an Empirical Orthogonal Functions (EOF; [4]) analysis has been carried out with the aim of identifying dominant patterns of variability in a multivariate data set in space and time. The spatial modes represent characteristic patterns as recurrent structures on a map, and the associated time series indicate how the intensity of these patterns varies over time. This technique is based on the calculation of the covariance matrix of the data, from which the eigenvalues, which indicate how much variance each pattern explains, and the eigenvectors, which represent the associated spatial patterns, are obtained. The resulting modes are orthogonal to each other, therefore they are uncorrelated, and by identifying only the first main modes, most of the variability in the data can be explained, thus reducing the complexity of the analysis. In this case the NAO corresponds to the first EOF mode of winter SLP anomalies in the North Atlantic-European (NAE) sector and thus largely explains regional climate variability.

The analysis employs 75 years of ERA5 and 250 years for each simulation. The latter were performed with the climate model EC-EARTH version 3, and consist in a free-running coupled simulation (COUPLED) and an atmosphere-only simulation (ATM-ONLY) with observed climatological SST and sea ice prescribed; both with radiative forcing fixed at year 2000 [5]. The datasets contain information for all terrestrial coordinates but the area of interest is limited to latitudes from 20°N to 90°N and longitudes from 90°W to 40°E. The average DJF for each year is calculated, providing the interannual variability, in other words, how winter conditions change from one year to the next. Climatology is then calculated by averaging all DJF values to obtain a climatic reference field, from which anomalies are determined by subtracting this average from the winter data.

Figure 1 shows the winter SLP climatology. In these maps, the centers of action of the NAO, namely the Azores High and the Icelandic Low, are clearly visible, highlighting the regions where most of the SLP variability is concentrated. The variability of these centers of action plays a critical role in modulating atmospheric dynamics and precipitation patterns over the NAE sector. A linear regression fit is applied to the anomaly time series at each spatial point removing the linear trend. The standard deviation is then calculated using detrended data, and is displayed in Figure 2. It is a statistical measure that quantifies the amount of variability or dispersion in a dataset. It is calculated as the square root of the variance. By computing the standard deviation along the time axis, we obtain a spatial map of interannual variability in SLP, which highlights regions with consistent or highly fluctuating pressure patterns over the years. This statistical measure helps to identify areas influenced by atmospheric dynamics such as the NAO. Detrended anomalies are transformed into a square matrix which is diagonalised to extract eigenvectors and eigenvalues representing the main patterns. A weight function is added to compensate for differences in area between latitudes, since the area is larger at the equator than at the poles. The first eigenvalue is associated with the NAO and explains approximately 40-50% of the SLP variability. With the NAO index, calculated from the first eigenvector as standarized time-series, it is possible to determine how much influence the NAO has on pressure, temperature and precipitation anomalies, allowing for a more detailed analysis of climate data. The analysis is based on linear regressions onto the NAO index, and statistical significance is assessed with a two-tailed Student's t-test for correlation at 95% confidence level.

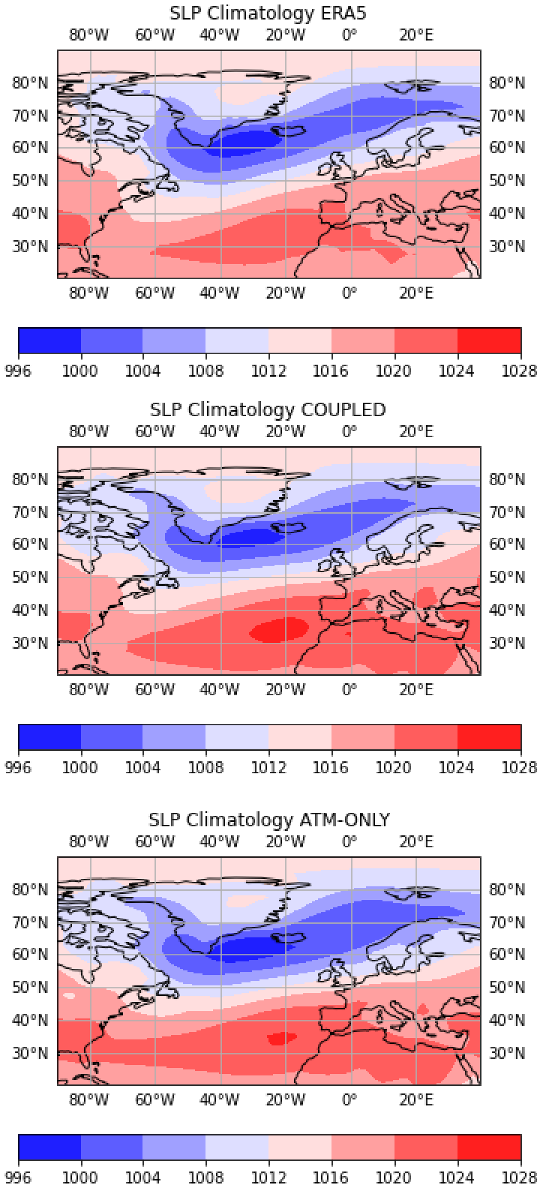

FIG. 1: Climatology of SLP [hPa] in boreal winter across datasets: ERA5 (top panel), COUPLED (middle panel), and ATM-ONLY (bottom panel). Climatology refers to the average state of a variable over a specific period, in this case, boreal winter, and provides a baseline against which anomalies are determined.

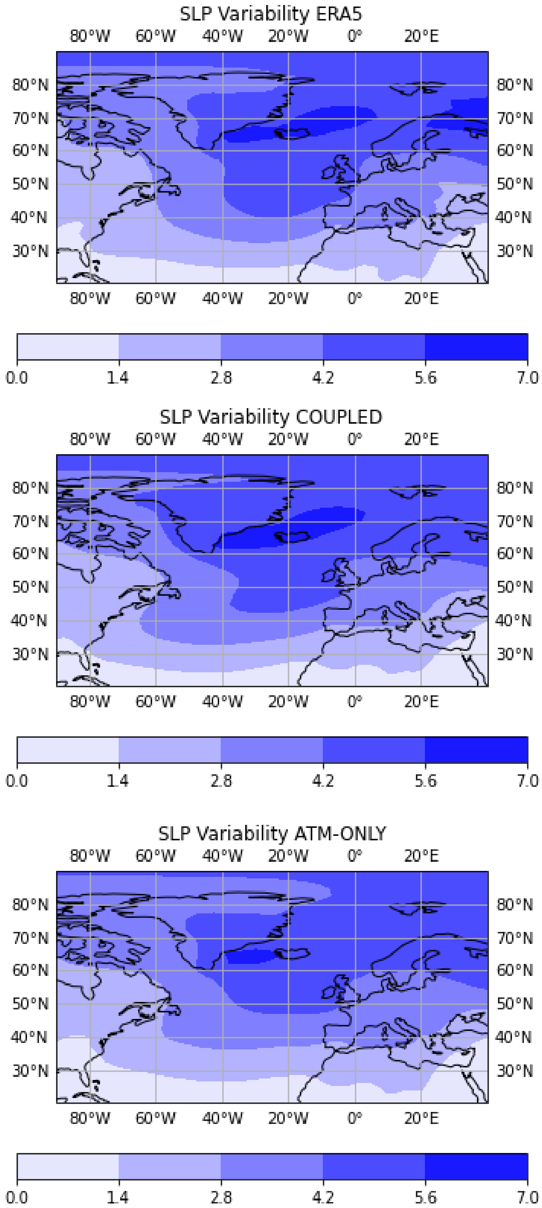

FIG. 2: Variability of SLP [hPa] for boreal winter across datasets. The top panel shows SLP variability in the ERA5 dataset. The middle panel depicts SLP variability in the COUPLED simulation. The bottom panel corresponds to SLP variability in the ATM-ONLY simulation. The spatial distribution highlights regions of large variability, particularly over the centers of action associated with the NAO.

III. RESULTS

In this section we present results derived from the analysis of SLP, two-metre surface temperature (T2M) and precipitation (PT) for the three datasets considered: ERA5, COUPLED and ATM-ONLY. These results illustrate how the NAO behaves in relation to these climatic variables and will allow us to explore whether it is mainly an atmospheric phenomenon or the result of atmosphere-ocean interaction (i.e. interactive ocean). All figures have a correlation contour (black line) which indicates statistically significant values (see Section II).

A. ERA5

In the top panel of Figure 3 the SLP is depicted and we can see how for NAO^{+} the climatological pressure gradient is reinforced due to the intensification of both the Azores anticyclone and the low pressure over Iceland. In the Icelandic Low the air rotates cyclonically while in the Azores High it rotates anticyclonically, causing the intensification of the westerly winds, which carry storm systems and moisture towards higher latitudes, in other words, towards northern Europe. It also shows a percentage, which indicates how much of the total SLP variability is explained by the NAO. We can see how almost half of the variance is due to this climate phenomenon thus illustrating its importance. The transport of moist air towards northern Europe generates significant increases in precipitation in this region, resulting in wetter winters. In contrast, southern Europe and the Mediterranean experience decreases in precipitation, resulting in drier winters. This anomalous precipitation pattern can be seen in the middle panel of Figure 3. In the bottom panel of Figure 3, we can see that the temperature anomalies form a quadrupole manifested in four main regions. Warm temperatures are present over northern Europe and the Eurasian Arctic because the anomalous westerly winds transport warm air from the Atlantic towards northern Europe and Scandinavia, causing positive temperature anomalies in these regions. Cold temperatures are found over Greenland and the American Arctic, where the cyclonic circulation associated with the Icelandic Low favors the advection of cold air from the Arctic, leading to negative temperature anomalies. Warm temperatures appear over the western subtropical Atlantic and eastern North America due to the strengthening of the Azores High, which induces warm advection in this region. Finally, cold temperatures are observed over the Mediterranean and the Middle East because of the anomalous north eastern cold advection there. As a result, there are mild winters in northern Europe, extreme cold in Greenland and drought and cold temperatures in Southern Europe.

B. COUPLED and ATM-ONLY

The previous analysis and description of the observed climate anomalies associated with the NAO (Figure 3) is valid for the simulated climate anomalies in both COUPLED (Figure 4) and ATM-ONLY (Figure 5). In order to determine whether the NAO is primarily a phenomenon internal to the atmosphere, these two datasets have been analysed. We can see how in both Figure 4

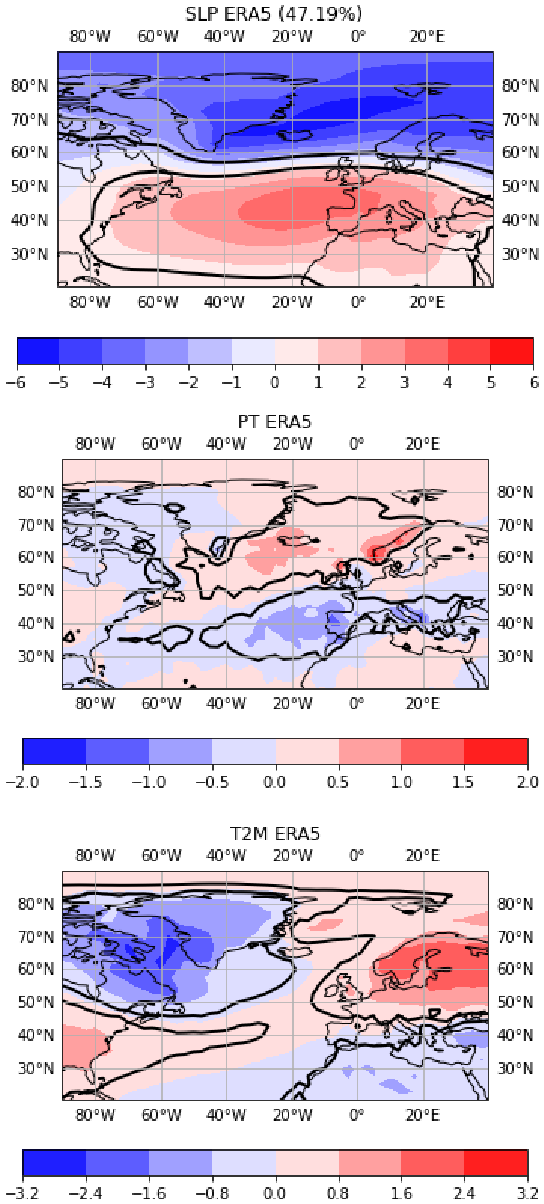

FIG. 3: Analysis of ERA5. The top panel shows the NAO^+ pattern in SLP [hPa], with 47.19% of the variability explained. The middle panel represents precipitation anomalies [mm/day], depicting the canonical dipolar pattern. The bottom panel displays the 2-meter temperature distribution [°C], highlighting the characteristic quadrupolar pattern. The contour indicates statistically significant areas in all panels.

and Figure 5, the SLP patterns associated with the NAO are very similar in terms of shape, location and amplitude. The percentage of SLP variability is similar in both configurations, 46.05% for COUPLED, and 40.55% for ATM-ONLY indicating that the main mechanisms of variability in the NAO do not depend significantly on the atmosphere-ocean coupling. The characteristic temperature quadrupole of the NAO appears clearly in both simulations and they are similar in intensity and distribution. The same is true for precipitation anomalies. This suggests that the NAO is an internal phenomenon of the atmosphere that does not strongly depend on the interaction with an active ocean.

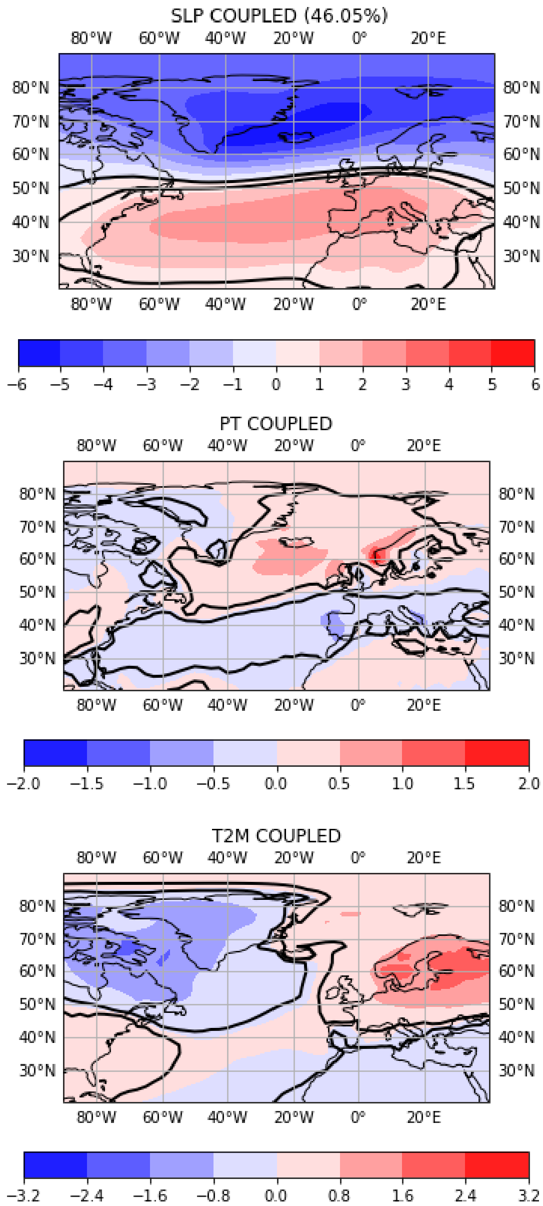

FIG. 4: Analysis of COUPLED. The top panel shows the NAO^+ pattern in SLP [hPa], with 46.05% of the variability explained. The middle panel displays precipitation anomalies [mm/day], depicting the canonical dipolar pattern. The bottom panel represents the 2-meter temperature distribution [°C], highlighting the characteristic quadrupolar pattern. The contour indicates statistically significant areas in all panels.

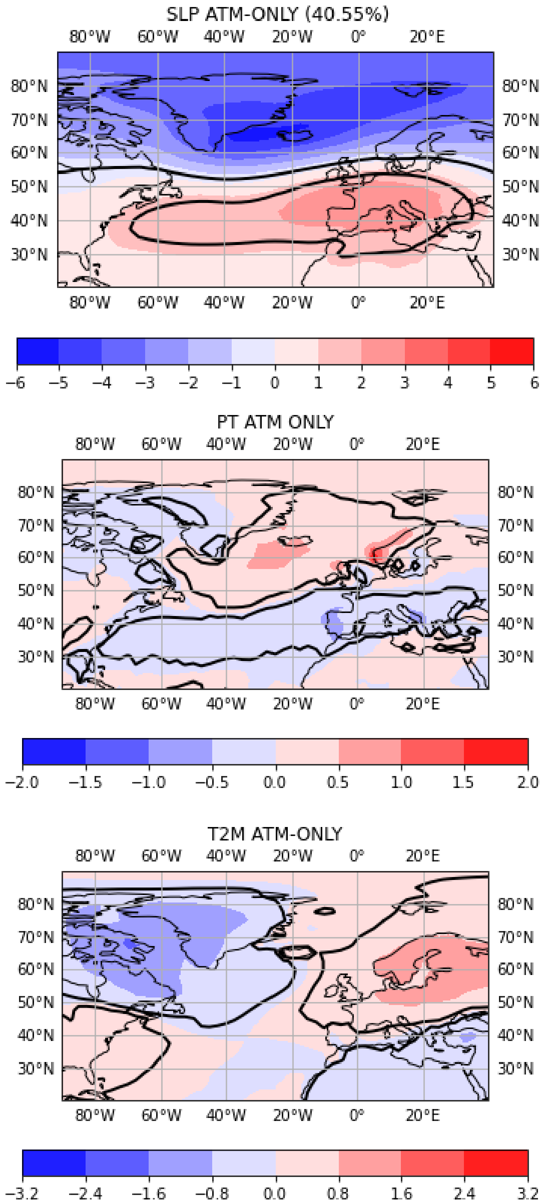

FIG. 5: Analysis of ATM-ONLY. The top panel shows the NAO^{+} pattern in SLP [hPa], with 40.55% of the variability explained. The middle panel displays precipitation anomalies [mm/day], depicting the canonical dipolar pattern. The bottom panel represents the 2-meter temperature distribution [°C], highlighting the characteristic quadrupolar pattern. The contour indicates statistically significant areas in all panels.

IV. CONCLUSIONS

The results of this study illustrate the NAO significance as the primary driver of winter climate variability in the North Atlantic-European region. The analysis show that the NAO explains nearly 50% of SLP variability during boreal winter, with characteristic anomalous patterns of temperature and precipitation linked to its phase. Both the COUPLED and ATM-ONLY simulations yield results consistent with ERA5, confirming the atmospheric origin of the NAO. The presence of the main NAO features without the need of ocean coupling emphasizes that the phenomenon is primarily atmospheric. The anomalous temperature quadrupole pattern and precipitation dipole reveal the extensive NAO climatic influence, impacting ecosystems, water management, and human activities over Europe because variations in the NAO can alter water availability for irrigation and consumption, agricultural production, and vulnerability to extreme weather events such as floods or droughts. This teleconnection pattern not only affects regional climate but also has significant global repercussions, as the NAO fluctuations influence atmospheric circulation in other parts of the world [3]. In summary, this study highlights the crucial importance of the NAO as a key phenomenon for regional climate prediction and management in the North-European Atlantic region. Further understanding its characteristics is essential for developing more accurate climate models and for planning policies that can mitigate climate impacts in the affected regions.

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Resum: L'Oscil·lació de l'Atlàntic Nord (NAO) és un fenomen atmosfèric clau que modela els patrons climàtics d'hivern a l'hemisferi nord, afectant la pressió del nivell del mar, la temperatura i la precipitació. Aquest estudi explora la NAO utilitzant dades de reanàlisi ERA5 i simulacions acoblades atmosfera-oceà i només atmosfera per analitzar-ne la dinàmica i els impactes. L'anàlisi de Funció Ortogonal Empírica identifica la NAO com el mode dominant de variabilitat, explicant fins al 50% de les variacions de la pressió del nivell del mar a la regió Atlàntic Nord-Europeu durant l'hivern boreal. Els resultats il·lustren que la NAO és principalment un fenomen atmosfèric, independent de l'acoblament oceànic, com es demostra pels patrons consistents entre conjunts de dades. L'estudi destaca el paper crucial de la NAO en la modulació dels patrons regionals de precipitació i temperatura, amb implicacions significatives per a la recerca climàtica i els sectors socioeconòmics.
Paraules clau: Geofísisca, dinàmica de fluids, clima, processos atmosfèrics
ODSs: Aquest TFG està relacionat amb els Objectius de Desenvolupament Sostenible (SDGs) 6,7,11,13,14,15.

Objectius de Desenvolupament Sostenible (ODSs o SDGs)

1. Fi de la es desigualtats		10. Reducció de les desigualtats	
2. Fam zero		11. Ciutats i comunitats sostenibles	X
3. Salut i benestar		12. Consum i producció responsables	
4. Educació de qualitat		13. Acció climàtica	X
5. Igualtat de gènere		14. Vida submarina	X
6. Aigua neta i sanejament	X	15. Vida terrestre	X
7. Energia neta i sostenible	X	16. Pau, justícia i institucions sòlides	
8. Treball digne i creixement econòmic		17. Aliança pels objectius	
9. Indústria, innovació, infraestructures			

La NAO està estretament vinculada a diversos ODS, ja que aquest fenomen climàtic influeix significativament en els patrons meteorològics d'Europa i l'Atlàntic. En l'ODS 6, la NAO impacta directament la disponibilitat i qualitat de l'aigua, condicionant pluges, sequeres, gestió d'aqüífers i ecosistemes aquàtics. És essencial per millorar la qualitat de l'aigua i implementar sistemes de gestió integrada, es relaciona amb les fites 6.1, 6.4 i 6.6. En l'ODS 7, la variabilitat climàtica causada per la NAO afecta la generació d'energia renovable, especialment l'eòlica i l'hidràulica, i contribueix a les fites 7.2 i 7.a. Pel que fa a l'ODS 11, els impactes climàtics de la NAO, com pluges extremes, sequeres o onades de calor i fred, afecten la resiliència urbana i les infraestructures. També pot intensificar riscos de desastres urbans com inundacions o danys per vents forts, contribuint als subobjectius 11.5 i 11.6. En relació amb l'ODS 13, comprendre el funcionament de la NAO ajuda a desenvolupar models per a la mitigació i adaptació al canvi climàtic, i és útil en l'elaboració de polítiques d'alerta primerenca i mesures adaptatives. Aquesta contribució s'alinea amb les fites 13.1, 13.2 i 13.3. L'ODS 14 també es veu influït, ja que la NAO afecta els corrents oceànics, la salinitat i temperatura de l'aigua, impactant la biodiversitat marina i els ecosistemes costaners. Aquesta relació està connectada amb els subobjectius 14.1, 14.4 i 14.5. Finalment, en l'ODS 15, els canvis climàtics associats a la NAO afecten la biodiversitat terrestre, contribuint a les fites 15.1 i 15.3.

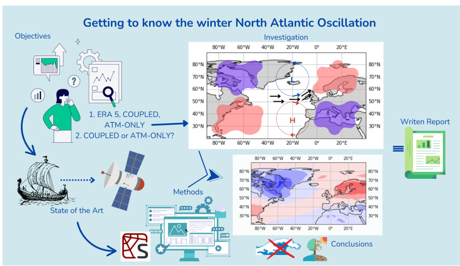

FIG. 6: Visual abstract of this TFG