Mapping the Impact of Climate Change on Indicators of Acoustic Propagation in the Atlantic Ocean

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Abstract: *Climate change is causing a significant warming of the seas and oceans, leading to changes in temperature and salinity distributions within the water column. The sound-speed-profile (SSP) depends on these distributions, and its vertical shape affects the acoustic propagation inside the water column. However, making inferences on the impact of climate change on acoustic propagation is not straightforward. In order to increase our understanding of this complex relationship, this paper presents a case study on propagation in the Atlantic Ocean. It considers the effect of climate change on indicators of acoustic propagation such as the sonic layer depth, sound channel axis, and convergence zones. Based on (horizontally) high-resolution climate modelling projections, maps are created that reveal how the sonic layer depth and channel axis might evolve over time up to 2050. By coupling the climate data with ocean acoustic propagation models, similar maps for convergence zone distances can be created. Maps of these properties provide insights into latitudes and longitudes where the effects of climate change on acoustic propagation are the strongest and in which regions a limited effect is expected. An outlook is given on the validity of historical databases.*

Keywords: *Climate change, sonic layer depth, sound channel axis, convergence zone, Atlantic Ocean*

1. INTRODUCTION

Climate change is causing a significant warming of the seas and oceans [1], and leading to changes in temperature and salinity distributions within the water column. The underwater propagation of sound depends on the sound speed profile of the water column, as well as on the sea surface and sediment conditions [2] [3] [4]. The propagation of sound is important for signal modelling, noise mapping, and sonar performance. Therefore, it is necessary to know and understand if the changing climate influences the acoustic propagation and to what degree. In addition, it tells how valid historical databases such as the World Ocean Atlas [5] are.

Previous studies that investigated the effect of climate change on underwater acoustics [6] [7] [8] focused on case studies that were relatively localized in space. It showed that in specific environments there is an impact of the changing climate on the underwater acoustics; such as the appearance of new ducts, changes in long range propagation in the arctic, and that the ambient noise may change even without significant changes in sound speed profiles. However, the propagation is influenced by not only the environment, but also the chosen source and receiver depths, which complicates its study and analysis.

In this paper, we present a case study on the effect of the climate change on indicators of acoustic propagation in the Atlantic using environmental data from climate models. The acoustic properties investigated are the sonic layer depth, the channel axis depth, and the convergence zone lengths.

First background information is given on the chosen indicators, followed by an explanation on the area of interest, the used climate model data, and how the indicators can be computed from the climate data. Then the results are displayed and commented on. Finally, a conclusion is given on the presented data and figures.

2. BACKGROUND INDICATORS OF ACOUSTIC PROPAGATION

The sonic-layer-depth (SLD) is the vertical distance from the ocean surface to the depth of the sound speed maximum [9]. This generally coincides with the mixing layer depth, a region for which the seawater mixes and the temperature and salinity are almost constant. The sound speed is a function of temperature, salinity, and pressure. Hence, the end of the mixing layer generally coincides with a (local) sound speed maximum. The SLD is of interest, as it characterizes acoustic surface ducts [9].

Below the mixing layer depth there is generally a sharp decline in the ocean’s temperature resulting in decreasing sound speed. At some point, the water column has a constant temperature all the way down to the bottom. This part of the water column is called the deep isothermal layer [10]. At the top of the isothermal layer, there is the sound speed minimum, usually referred to as the sound channel axis (SCA). The SCA is of interest, as it allows long-range propagation of sound.

The convergence zone distance is the horizontal distance between a source and a receiver point (at the same depth) for which high levels of sound occur. A necessary requirement for a convergence zone to exist is that rays may not interact with the sediment, as this would break up caustics [11]. This requirement is achieved by the existence of a so-called critical depth [10], a depth deeper than the SCA, whose sound-speed equals the sound-speed maximum for depths smaller than the SCA.

3. METHOD

3.1. Area of interest and climate models

The chosen area of interest is the Atlantic Ocean between -75 to 15 degrees of longitude and 10 to 68 degrees latitude in steps of 4 degrees in latitude, and 5 degrees in longitude. Points with water depth shallower than 1000 m were ignored, as well as points in the Mediterranean Sea. Two months of interested are chosen: March and September. These are assumed to be the coldest and warmest months respectively.

In this study, temperature and salinity profiles were used at the latitude-longitude position of each grid cell. These profiles were combined with the depth and an equation [13] to get the sound-speed profile (SSP) at each grid cell. The profiles come from climate model data belonging to CMIP6 [14] [15] and following the Shared Socio-economic Pathway 5-8.5 scenario [12]. Three models were used: CNRM-CM6-1 [16], EC Earth3P [17], and HadGEM3-GC3 [18]. Monthly averaged climate model data was selected in the time range from 1971 to 2050.

3.2. Calculating the Indicators of Acoustic Propagation

Sound channel axis (SCA)

After having determined the SSP, the sound channel axis is determined by identifying the depth of minimum sound-speed. In some cases, especially close to the arctic or Greenland, the sound-speed minimum occurs at, or close to, the air-water interface.

Sonic layer depth (SLD)

The sonic layer depth is the depth for which the sound-speed profile reaches a local maximum (due to a mixing creating a more-or-less constant temperature and salinity in the top layer of the water column) [10]. This local maximum is the first local maximum between the sea-surface and the channel axis, assuming that there is a well-mixed top layer.

Convergence zone length (CZ length)

It is not trivial to choose a source depth in computations to determine the distance at which a convergence zone happens. However, if a convergence zone is present, it is known that there is a critical depth, at which the rays must travel (almost) horizontally. This effect can be exploited to find the convergence zone distance as follows:

1. Determine the SCA depth.
2. Determine the maximum SSP above the SCA depth (uSSPmax).
3. Check whether there exists a critical depth.
   - If there is none, then there can be no convergence zone.
4. Place a source at the critical depth and simulate some acoustic rays that leave the source almost horizontally. Trace these rays through the water column.
5. Check at what distance the rays return to this depth and orientation and save this distance.

3.3. Combining the results

The SCA, SLD, and CZ length, are all computed using the three climate models. Furthermore, as specific years could be outliers, it is important to consider the results of a group of years together. Therefore, statistics is applied to the datapoints. For each month, the three models give different results for the SCA depth, SLD, and CZ lengths. It was chosen to pick the median value of the three, assuming that Nan's (Nan=Not a number) are ignored (for example a Nan can occur when there is no convergence zone). The next step is combining the results of a set of years. In this work the results of 20 years are combined, by taking the mean. The occurrences of the finite values are recorded on the model level. If only one out of the three models result in a convergence zone of length L, then L is reported as the convergence zone length for that position. However, the occurrence for that position and year is only equal to 1/3.

4. RESULTS AND DISCUSSION

4.1. Sound channel axis depth

For the month of March, it can be observed that the SCA does not vary much in the period of 1971-1990 and 2031-2050 for most latitudes below 45 degrees, as can be seen in Fig. 1. For this part of the ocean, the SCA depth is between 800 and 1600 m which is deeper than the areas most affected by climate change [19]. Above the 45 degrees latitude, there are large changes in the second period with changes up to 50% in positive and negative directions compared to 1971-1990, with the largest changes between the coast of Canada up to the Reykjanes Ridge and Greenland. This area is where the ocean gets an influx of cold fresher water due to melting of ice.

Although it is not shown, similar results can be obtained for other months such as September. The major difference between the two months is the direction of the percentual changes.

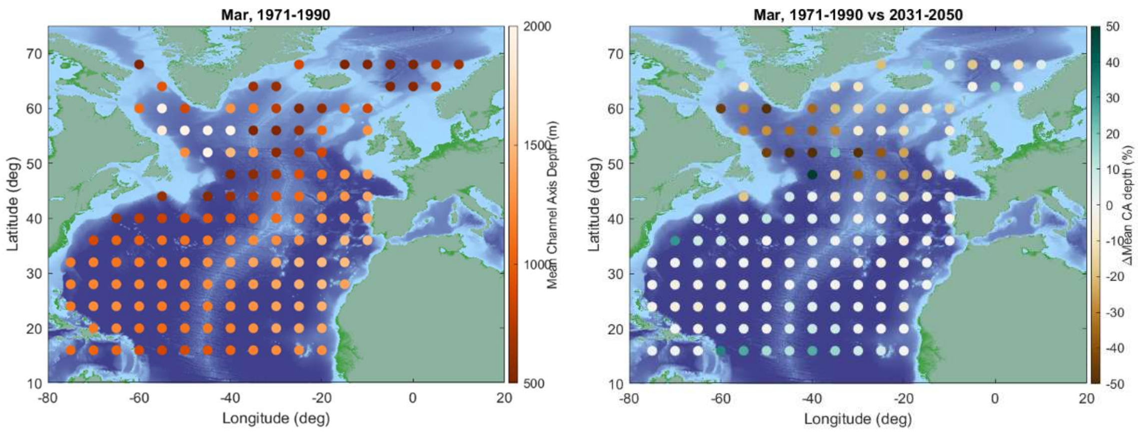

Fig.1: Map of the channel axis depth in the Atlantic Ocean for the month of March. Left: average from 1971 to 1990. Right: percentual variation for the time bracket of 2031-2050 compared to 1971-1990.

4.2. Sonic layer depth

The sonic layer depth can only exist if there is a good mixed surface layer, where the sound can get trapped. As can be seen in Fig 2, the SLD decreases over time for most of the Atlantic in March. Even though the SLD decreased for the most part of the Atlantic Ocean, there is an exception South of Greenland, where there is a region with a strong increase in the SLD, between 10% and 50%.

During the summer, it can happen that the increase in sea surface temperature leads to a (small) gradient of warmer water near the surface to colder water near the end of the mixing layer. This then leads to a negative gradient in the sound-speed-profile. The result is that there are months in the year for which there is no sonic layer. In our study, the sonic layer depth completely disappears for only two locations off the coast of west Africa in March. However, in September there is almost nowhere a SLD because the sea surface temperature is too high.

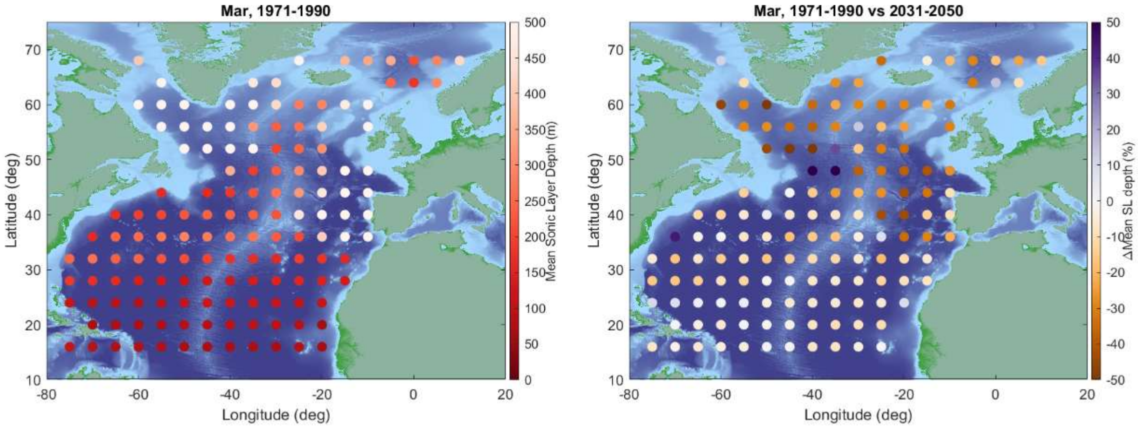

Fig.2: Map of the sonic layer depth in the Atlantic in March. Left: average from 1971 to 1990. Right: percentual variation for the time bracket 2031-2050 compared to 1971-1990.

4.3. Convergence zone length

Fig. 3 shows a map of the CZ lengths for both the month of March and September, and their percentual changes from 1971-1990 to 2031-2050. The first observation is that during March there is a higher variability in the CZ lengths than in September in the period 1971-1990. The percentual changes are also larger in March than in September. Furthermore, it can be observed that along the Atlantic ridge and around Greenland and Iceland (both regions where the ocean is shallower), there are more instances in which a CZ cannot exist in September. This effect will be even stronger for the period 2031-2050 and is caused by the surface temperature increasing too much. The critical depth does not exist anymore, and the sound interacts with the bottom.

For the locations that have a convergence zone in the future, there is no clear pattern for the increase or decrease in its length in the month of March. For September, there is an overall slight increase in the CZ length.

Fig. 4 shows the average CZ length (left) for all the considered data points as well as the total occurrence of a CZ (right) and it also shows these variables for only the datapoints at a latitude above or equal to 45 degrees. For the Atlantic Ocean as a whole, only a minor trend is visible where the average lengths seem to converge irrespective of the month. The opposite is happening for the higher latitude area, where the CZ lengths seem to diverge between the months; for March the lengths become shorter and for September the lengths become larger (Fig. 4, left panel).

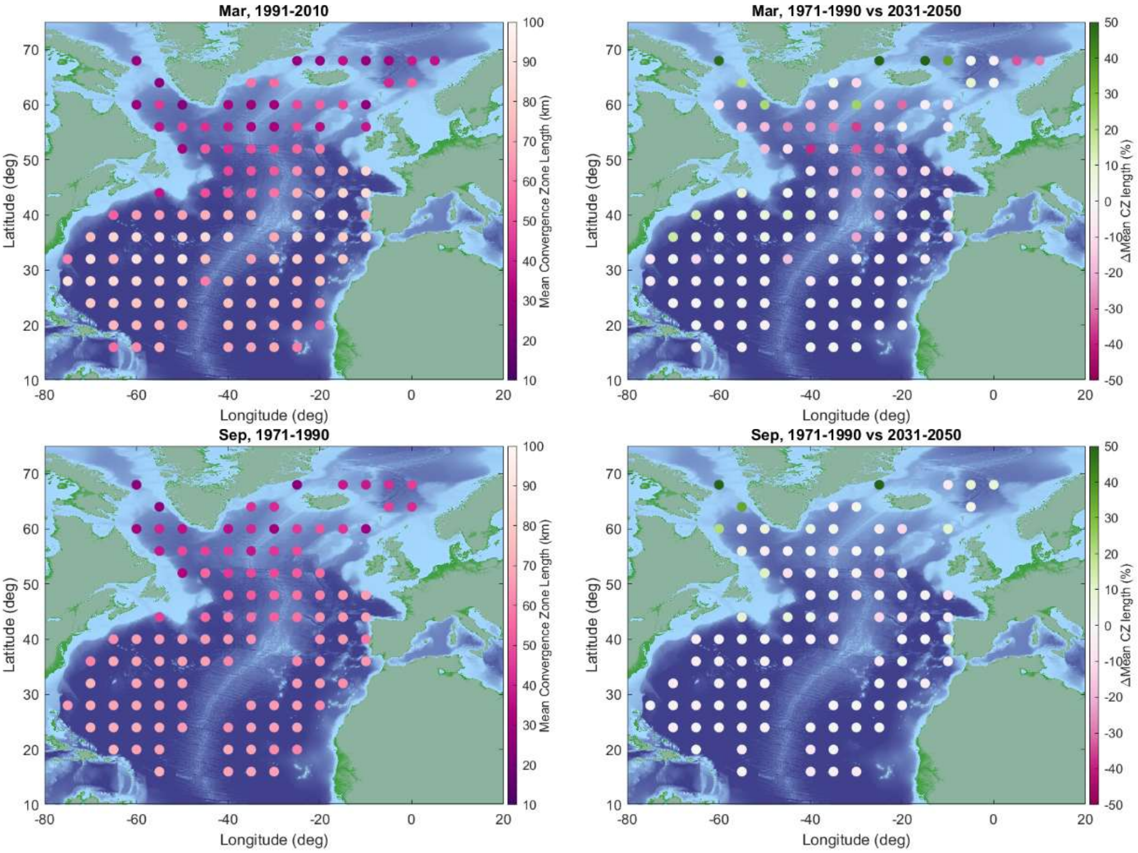

Fig.3: Map of the convergence zone lengths in the North Atlantic. Left: average from 1971 to 1990. Right: percentual variation for the time bracket 2031-2050 compared to 1971-1990. Top: March. Bottom: September.

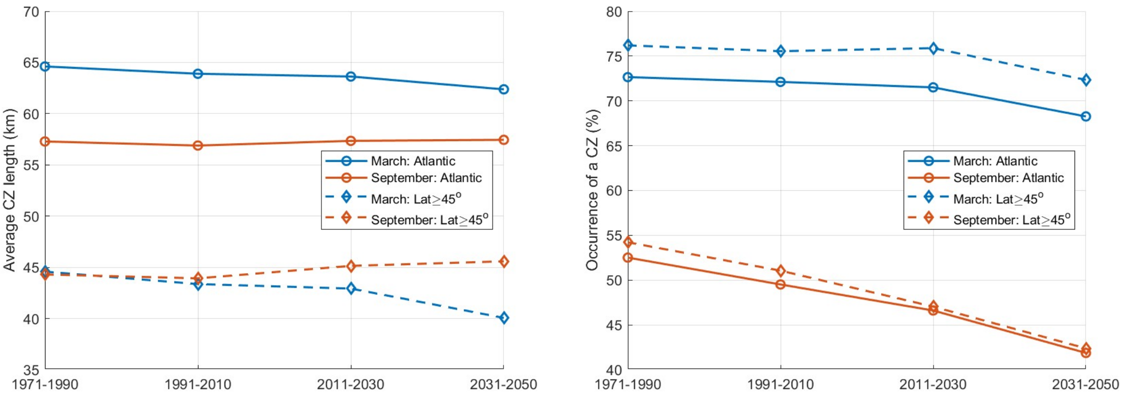

Fig.4: Left: Average of the Convergence Zones lengths over the Atlantic and for latitudes over 45 degrees. Error bars are relatively large and are not plotted here. Right: Occurrence (on a model-based level) of convergence zones in the Atlantic and for latitudes over 45 degrees.

It is also observed that the occurrence of convergence zones decreases over time, meaning that convergence zones will happen less often (Fig. 4, right panel). This phenomenon happens for both months and is not restricted to the higher latitudes. This is attributed to a warming of the sea surface resulting in a critical depth occurring less frequently.

These results for the CZ lengths have implications for the use of historical databases. Databases such as the WOA are 20 years monthly and seasonal averages. Depending on what part of the Atlantic Ocean one is interested in, the validity of such a database may no longer apply in modern or future scenarios. This is especially true for the higher latitudes.

5. CONCLUSIONS

This study shows how it is possible to use temperature and salinity profiles from climate models to compute indicators of acoustic propagation, such as the sound channel axis depth, sonic layer depth, and convergence zone lengths.

Analyses based on three climate models show that the sound-channel axis depth varies mostly for latitudes higher than 45 degrees between the period of 1971-1990 and 2031-2050. This is because the sound channel axis is generally shallower at these latitudes, and the heat still penetrates to these depths.

The sonic layer depth changes across the whole Atlantic with a general decrease in its depth in March, which has implications for acoustic propagation in the surface duct.

Finally, the convergence zones were analysed. The effects of climate change for the month of March are stronger than the month of September. In September there is a marginal increase in the convergence zone length between the two periods, whereas in March no general statements could be made for the Atlantic. Analysis showed that for latitudes above 45 degrees there is a trend in the length of the convergence zone, where it shortens in March and increases in September. If the length variation differs depending on the month, the occurrence of convergence zones decreases over time, for both March and September, due to increasing sea surface temperatures.

The implications for historical databases depend on the application. For latitudes below 45 degrees, historical databases can still be used to compute the sound channel axis. Concerning the latitudes above 45 degrees, for the sonic layer depth or the convergence zone length, one will make errors if uses historical database too outdated.

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REFERENCES

[1] **H. Pörtner, D. Roberts, V. Masson-Delmotte, P. Zhai, E. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama and N. Weyer**, *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate - Tehnical Summary*, IPCC, 2019.

[2] **L. Brekhovskikh and Y. Lysanov**, *Fundamentas of Ocean Acoustics*, Moscow: AIP Press, Springer, 2003.

[3] **M. Ainslie**, *Principles of Sonar Performance Modeling*, Heidelberg: Springer, 2010

[4] **F. Jensen, W. Kuperman, M. Porter and H. Schmidt**, *Computational Ocean Acoustics*, Springer, 2011.

[5] **J. Reagan, T. Boyer, H. García, R. Locarnini, O. Baranova, C. Bouchard, S. Cross, A. Mishonov, C. Paver, D. Seidov, Z. Wang and D. Dukhovskoy**, *World Ocean Atlas 2023*, NOAA National Centers for Enviornmental Information, 2024.

[6] **L. Possenti, G. d. N. L. Reichart, F. Lam, C. de Jong, M. Colin, B. Binnerts, A. Boot and A. von der Heydt**, *Predicting the contribution of climate change on North Atlantic underwater sound propagation*, PeerJ, pp. 1-26, 2023.

[7] **K. Pelekanakis, A. Kondi, A. Russo and S. Carniel**, *Simulation of Climate Change Impact on Underwater Acoustic Transmission Loss*, in IEEE/MTS OCEANS, Singapore, 2024.

[8] **V.O. Oppeneer, N. Risser, R. van Vossen, K. Pelekanakis, G. Giroli and A. Russo**, *The Impact of Climate Change on Sonar Performance: A case study in the high north*, in ICUA, Bath, UK, 2024.

[9] **R. Helber, C. Barron, M. Carnes and R. Zingarelli**, *Evaluating the sonic layer depth relative to the mixed layer depth*, Journal of Geophysical Research: Oceans, 113 (C7), pp. 1-14, 2008.

[10] **P. Etter**, *Underwater Acoustic Modeling and Simulation*, Boca Raton, FL: CRC Press, 2018.

[11] **R. Urick**, *Principles of underwater sound*, 3rd ed., New York: McGraw-Hill, 1983.

[12] **R. Keywan et al**, *The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview*, Global Environmental Change, 42, pp. 153-168, 2017.

[13] **K. Mackenzie**, *Nine-term Equation for Sound Speed in the Oceans*, Journal of the Acoustical Society of America, 70, pp. 807-812, 1981

[14] **R. j. Haarsma et al.**, *High resolution model intercomparison project (highresmip v1.0) for CMIP6*, Geoscientific Model Development, 9 (11), pp. 4185-4208, 2016.

[15] **V. Eyring et al.**, *Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization*, Geoscientific Model Development, 9 (5), pp. 1937-1958, 2016.

[16] **A. Voldoire et al**, *Evaluation of CMIP6 DECK Experiments With CNRM-CM6-1*, Journal of Advances in Modeling Earth Systems, 11, pp. 2177-2213, 2019.

[17] **R. Döscher et al**, *The EC-Earth3 Earth system model for the Coupled Model Intercomparison Project 6*, Geosci. Model Dev., 15, pp. 2973-3020, 2022.

[18] **K. Williams et al**, *The Met Office Global Coupled Model 3.0 and 3.1 (GC3.0 and GC3.1) Configurations*, Journal of Advances in Modeling Earth Systems, 10, pp. 357-380, 2017.

[19] **J. Abraham, M. Baringer, N. Bindoff, T. Boyer, L. Cheng, J. Church and J. Conroy**, *A review of global ocean temperature observations: Implications for ocean heat content estimates and climate change*, Rev. Geophys, 51 (3), pp. 450-483, 2013.