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Review

A Review of Ocean Dynamics in the North Atlantic: Achievements and Challenges

Knut Lehre Seip

Faculty of Technology, Art and Design, Oslo Metropolitan University, N-0130 Oslo, Norway; knut.lehre.seip@oslomet.no; Tel.: +47-67238816

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Abstract: I address 12 issues related to the study of ocean dynamics and its impact on global temperature change, regional and local climate change, and on the North Atlantic ecosystem. I outline the present achievements and challenges that lie ahead. I start with observations and methods to extend the observations of ocean oscillations over time and end with challenges to find connections between ocean dynamics in the North Atlantic and dynamics in other parts of the globe.

Keywords: North Atlantic; ocean dynamics; time series analysis; North Atlantic oscillation; Atlantic multidecadal oscillation; Atlantic meridional overturning circulation; NAO; AMO; AMOC

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1. Introduction

The two most recent pre-industrial eras of warm and cold climate, the Medieval Climate Anomaly (MCA) and the Little Ice Age (LIA), have both been linked to North Atlantic ocean variability, e.g., Trouet et al. [1]. The first era is the most recent natural counterpart to the post-industrial climate warming, and the last era indicates a natural cold state for the climate. Furthermore, from about 1880, there exist instrumental records that show three hiatus periods in global warming that were possibly due to natural forcing. Thus, the two historical periods and the hiatus periods have the potential of being useful in disentangling the effects of intrinsic and anthropogenic forcing. Climate studies depend upon reliable records of climate variations. In the present review, I outline results in the literature obtained by examining climate time series and the methods used to obtain both the records and the information that can be derived from them. Often there are alternative methods that can be used to address a particular issue, and I make a list of the methods. However, I do not try to evaluate their skills. I have tried to select studies that also give an outline of problems and issues that prevail in 2020.

2. Materials and Methods

I have examined papers that address issues related to ocean dynamics in the North Atlantic and its effects on climate, weather and ecosystems in the region. I have not been able to include all important contributions that deal with ocean dynamics in the North Atlantic and its effects, and, in particular, older contributions are only occasionally included.

3. Results

3.1. Observations

There are three major observation series of ocean variability in the North Atlantic. The North Atlantic Oscillation (NAO) (the instrumental records starting in 1821), is a series describing the mean sea level pressure difference at a station in the southern end of the North Atlantic (e.g., Lisbon) and one in Iceland [2]. The Atlantic Multidecadal Oscillation (AMO) indices measures the average sea surface temperature (SST) in the Atlantic North of Equator, starting in 1871 [3,4], while the Atlantic meridional overturning circulation (AMOC) indices were started in 2004 [5]. A compilation of the time series can be found online (https://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/).

3.2. Extending the Time Series

There have been several attempts to extend the instrumental recordings of the climate series further back in time. Cook et al. [6] extended the NAO series back to 910. Other attempts to extend the NAO were made by Jones et al. [2], Luterbacher et al. [7], and others. The AMOC was extended from 2004 to 1870 by Caesar et al. [5] The AMO was extended to 1567 by Gray et al. [8] and simulated over a 1400 year period by Knight et al. [9]

3.3. Methods for Extending the North Atlantic Instrumental Recordings

The instrumental recordings can be extended based on older instrumental records, or on the effects that the variables represented by the series may have on physical, chemical, or biological factors. For example, the AMO reconstruction by Gray et al. [8] was based on tree-ring data, and the NAO reconstruction by Trouet [1] was based on tree-ring data, as well as spelothem–based precipitation data. Stalagmite records have been used to extend North Atlantic climate records over three millennia [10]. Simulation models have been used by, for example, Knight et al. [9].

Challenges: there is a need to extend the North Atlantic instrumental recordings further back, in time to be able to calculate cycle times, and subsequently to compare high and low values of the series with climate events. One particular challenge is to find time series data that are (essentially) only affected by the same factors as the instrumental time series data.

3.4. Methods for Verifying Time Series Extensions

The most common method for verifying time series extensions is to compare patterns in the portion of the extended series that overlap with instrumental records. Least squares methods and their explained variance have been used by Cook et al. [6], Woollings et al. [11] and Trouet et al. [1] Other methods to verify that the extensions express the same phenomena as the original instrumental indexes are the multitaper method (MTM) or the wavelet power spectrum method (WPSM). They are applied to the observed and reconstructed series, to establish that both series show the same cycle lengths, e.g., Gray et al. [8] A fourth method is to examine if the extended series show the same lead-lag relations to other series as the original instrumental series [12].

Challenges: the most common method for inferring a causal effect is to run a regression between the candidate caus and the candidate effect. However, it would be an improvement to develop new methods that better take into account shifts between a causal series and a target series, that is just a function of time delays in the causal mechanisms.

3.5. Ocean Cycles

One of the reasons time series extension is important is that it would allow the calculation of ocean oscillation cycle lengths beyond short oscillations in the range allowed by the instrumental series. Some studies claim that the ocean time series show little cyclic variability and are mostly stochastic, e.g., Privalsky and Yushkov [13] and Mann et al. [14] Very short cycle lengths, less than seven time steps long, seem to be generated by two stochastic processes that interact [15,16]. Other studies identify both short and long cycles, $\approx$ 30–50 years in, e.g., the NAO [11,17–19]. Common cycle lengths of 3, 7, 18, 23, 29, and 37 years for ocean oscillations in the North Atlantic (the NAO), as well as in the Pacific, were identified by Seip and Gron [15]. The series is surprisingly close to the series of prime numbers and this would indicate that stochastic processes are involved. However, the amplitude of each component may vary with intrinsic or extrinsic factors. Cycle lengths on potentially intermediate time scales $\approx$1000 years have been discussed by Haskins et al. [20] Cycle lengths on paleontological time scales have been identified by Imbrie et al. [21] and others.

Challenges: as far as I know, only simulation results have been used to bridge the vacant space in cycle lengths between cycle lengths of, say 50–60 years, and the cycle lengths that are associated with orbital forced responses, that is, cycles in the order of kilo years (kyr). However, observation based methods are needed to verify the simulated results. The ocean variabilities that drive the climate are only partially established and may change as the global temperature increases, e.g., Li et al. [22] on the Pacific Decadal Oscillation. Alternatively, the climate changes with some yet unidentified variables. The AMOC is, for example, predicted to weaken in the 21st century, Little et al. [23], but the weakening may also be part of a still undefined cyclic movement.

3.6. Methods to Identify Ocean Oscillations and Their Lead—Lag Relations

Ocean cycles are identified by power spectral analysis (PSA) or versions of PSA, like wavelet spectrum methods [24,25], the multitaper method [13,14], or the bivariate empirical mode decomposition method [26]. The cycles appear to have teleconnecting character, thus candidate causes for regional oscillations may be found at "global" distances. Wang, Ting [27] introduces, for example, effects from El Nino Soutern Oscillation (ENSO) on the NAO. However, both these authors and Hurrell (2010) emphasize Arctic sea-ice concentrations as a possible additional driver of the NAO. Hurrell [28] and Hurrell and Deser [29] also invoke the internal, nonlinear dynamics of the extratropical atmosphere. There are also suggestions that volcanism may drive, or nudge, ocean oscillations, e.g., Birkel, Mayewski [30] on the AMO.

Lead-lag (LL)—relations between paired ocean oscillations can be found by, e.g., cross-correlation methods, e.g., Tatli and Menteş [31], Granger causality tests, that increase its skill with longer stationary series, e.g., Mosedale et al. [32], or by the LL- method by Seip and McNown [33], that do not require stationary series. Lead-lag relations between the AMO and the AMOC were studied by Clement, Bellomo [25]. They concluded, based on modeling results, that the AMOC could not be a driver of the AMO, because the AMO does not require the AMOC as a leading variable.

Challenges. It is a question if the oscillations really are oscillations, with some stationary characterstics, or if they just express some kind of variability that do not repeat itself over extended times. We do not really know what causes the cycles, or their amplitudes, but stochastic processes seem to play a role [25,29]. Since oscillations, as well as the polarity of LL- relations, appear to be synchronized in the North Atlantic and possibly beyond [34], it is a challenge to disentangle the effect of one variable from another solely on their regression skill or their LL- relations. Thus, new techniques are requiered.

3.7. Understanding and Explaining

An objective for the study of time series in the North Atlantic is to understand the processes that govern North Atlantic variability (oscillations), the North Atlantic climate, and the ecosystems. Robson et al. [35] link ocean circulation to heat transport and water density changes. Woollings et al. [11] examine blocking effects on ocean variability. The role of sequestration and emission of CO_2 from the North Atlantic is uncertain. Watson, Schuster [36] suggest that there are annual and decadal variatoins of CO_2 (proxie)-uptake of around 20%, and Guallart, Schuster [37] found bi-decadal trends in the storage rates of CO_2 in the deepest North Atlantic waters. Thomas, Prower [38] found that CO_2 uptake is associated with the NAO, and that it may correspond to NAO cycles over centennial periods. However, for CO_2 variations in the oceans to modulate CO_2 concentrations in the atmosphere, emissions and sequestrations have to be synchronized among all oceans. Gruber et al. [39] their Table 2 calculate uptake and loss of CO_2 from the oceans for the period 1994–2007, and Landschutzer et al. [40] show decadal variations in uptake and loss. There are also indications that there are mechanisms that could enhance ocean carbon storage [41,42].

Challenges: what causes the cycles and how cyclical are the cycles in the North Atlantic? What causes LL- relations between ocean cycles? Furthermore, what causes shifts between LL- relations? What are the respective roles of the atmosphere and the oceans and what are the relative roles of heat and heat storage and sequestering and emissions of climate gases, like CO_2 from the oceans? Is it possible to see a fingerprint of variations in atmospheric CO_2 concentrations from variations in CO_2 sequestration in the oceans?

3.8. Effects on Regional and Local Climate

Arthun et al. (2019) found that variable ocean heat transport governs Arctic winter sea variability. The Atlantic ocean forcings (the AMO) on the North American summer time climate are discussed by Enfield et al. [3], and Sutton and Hodson [43]. Ghosh et al. [44] discuss the impact of the AMO (nomenclature AMV) on the summer time climate in Europe. The impact of the NAO on European climate is explored by e.g., Hurrell and Deser [29] and Rousi et al. [45] The impact of the AMOC on the hiatus periods in global warming is studied by Chen and Tung [46] and Wei et al. [47] and a review of the impact of the AMOC on the U.S. East coast sea level was given by Little et al. [23].

3.9. Effects on Regional or Local Ecosystems

The northeast Atlantic mackerel fishery and the Atlantic Bluefin tuna have been associated with climate change by Hughes et al. [48] and Faillettaz et al. [49], respectively. Impacts on the North Atlantic salmon and plankton were studied by Beaugrand and Reid [50]. However, their results show that it is difficult to find significant relations between species abundance and ocean oscillations, except for relations between upward or downward trends over short time windows.

Challenges: when relations between fish abundance and climate are examined, the additional impact of fisheries is always a challenge. Most aquatic species will have an unimodal response to temperature, too low and too high temperatures decrease their abundance, e.g., [51] and [52] respectively. For fish species the match- mismatch effects between fish and its food source are important [53]. Furthermore, the higher up in (biological) trophic level, the more pronounced are the effects of dynamic chaos, [54,55] or patterns that just emerge as a result of the interaction between species interaction and seasonal fluctuations [56]. Thus, to distinguish patterns that are found during time periods comparable to the life span of a species from persistent patterns over longer periods is a challenge.

3.10. Predictions

An ultimate objective for global climate studies is to make predictions for future changes in the climate, so that one is able to prepare for changes that will affect ecology and our life on earth. Predictions are conveniently divided into those that relate “natural variables” to changes in the climate, and those that relate endogenous emission of greenhouse gases to the climate. Extending empirical models based on current time series, Wang, Ting [27], have one option, the modelling of future climate with scenarios that show increased anthropogenic emissions and increased CO_2 levels in the atmosphere is another option. In a recent study, the contribution from ocean dynamics in the Atlantic and the Pacific oceans have been estimated to be 30%, versus a contribution from greenhouse gases of 70% [19].

Challenges: how far back is it possible to use the cyclic nature of ocean oscillations to make predictions for temperature changes or changes in surface water levels? Does a network of teleconnections link the global oceans together? Can cycles with different cycle lengths be superimposed, such that the resulting superimposed cyclic pattern has predictive power? Alternatively, are various target variables affected by variables with different cycle lengths present in the same time series? How can complex simulation models and simple or multiple regression models (MR) be validated? Similar concerns apply to principal component analysis, PCA, factor analysis and similar techniques. (However, PCA may include both higher order polynomial expressions as well as interaction expessions between variables). In particular, least squares techniques require ideally that the observations are normally distributed and not serially correlated. If one of the series is almost a copy of the first series, but shifted along the x-axis, the explained variance of the regression do not give a correct picture of their relationship. Since most climate time series are cyclic, additional model tests could be used, like LL- relations, and the validation of pro- and counter cyclic patterns between paired series. A leading relation is a prerequisite for a causal effect on a target variable [55,57]. New methods that could be employed are a neural network [58], that does not require any functional forms to be decided on a priori, and an artificial intelligence method. There exist data that show climate conditions at very high CO_2 concentrations [59] (≈2000 ppm CO_2), but sea surface temperatures, or global temperature anomaly (GTA) values at those concentrations are, to our knowledge, still not available. The high CO_2 values are probably due to a very slow carbonate–silicate geochemical cycle [60], that are now "replaced" by much faster anthropogenic CO_2 emissions. Thus, to find out how warm the globe can be, or to find a relation between CO_2 and GTA, paleo-climate studies are relevant in current global climate studies [61,62].

3.11. Relations between the NAO, the AMO, and the AMOC.

Observed relations between the AMO, the AMOC and the NAO were compared to the modeling result by Gastineau et al. [63] In particular, the authors inferred LL- relations between the AMO and the AMOC. Clement, Bellomo [25], O'Reilly et al. [64], and Trenary and DelSole [65] discuss causal relations between the AMO and the AMOC. A generic overview of climate variability and the relations between ocean variability (oscillation) time series are given by Cassou et al. [66] Birkel, Mayewski [30] found that the AMO is driven by volcanic eruptions. However, Seip and Gron [34] show that there are synchronized and changing LL- relations between the NAO, the Southern oscillation index (SOI) and the PDO after about 1920.

Challenges: it appears that some frequencies in ocean oscillations are synchronized in the North Atlantic, and probably also over larger regions. Furthermore, their LL- relations also seem to be synchronized [12]. Thus, it is a challenge to disentangle the correct oscillations as possible causal agents for a target phenomenon.

3.12. Relations between Ocean Dynamics in the North Atlantic and Ocean Dynamics in other Regions

There are significant teleconnections among the great oceans. Zhang et al. [67] found a complex pattern of atmospheric teleconnections and subsequent ocean adjustments between the AMOC and the Southern ocean. Wu et al. [68] found that the Pacific decadal oscillation (PDO) and AMO show LL- relations.

Challenges. Although many studies show teleconnections among ocean oscillations frequently after some filtering and smoothing, there are no systematic overviews of frequencies that dominate in teleconnections.

The Special Issue on The North Atlantic Ocean Dynamics and Climate Change.

The two articles in this Special Issue discuss two important issues in North Atlantic Ocean dynamics. The article by Seip et al. [12] shows that the North Atlantic oscillations show distinct cycles, including the NAO that have been claimed to be a stochastic series. The article by Rousi et al. [45] shows that the NAO may have different flavors, i.e., have different westerly and easterly positions, and that the different flavors cause differences in European climate.

4. Discussion

Although there have been several important advances in the understanding of the North Atlantic climate system and its contribution to the global climate, it is probably too early to conclude that any of the issues discussed above have been firmly resolved (in toxicology, the term: "at the level of no concern" is used). In this paper, I have not included the issue of an increasing trend in global warming caused by anthropogenic forces. Some examples where I believe "the jury is still out" are the relative weight of natural versus anthropogenic forces on cycle frequencies in global temperature change; the causes of very long cycles (millennial scales) in global warming; and to which degree anthropogenic forces alter the "natural" cycles in global climate.

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References

1. Trouet, V.; Esper, J.; Graham, N.E.; Baker, A.; Scourse, J.; Frank, D.C. Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly. *Science* **2009**, *324*, 78–80. [CrossRef] [PubMed]
2. Jones, P.D.; Jonsson, T.; Wheeler, D. Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. *Int. J. Climatol.* **1997**, *17*, 1433–1450. [CrossRef]
3. Enfield, D.B.; Mestas-Nunez, A.M.; Trimble, P.J. The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophys. Res. Lett.* **2001**, *28*, 2077–2080. [CrossRef]
4. Rayner, N.A.; Parker, D.E.; Horton, E.; Folland, C.K.; Alexander, L.V.; Rowell, D.; Kent, E.; Kaplan, A. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res. Atmos.* **2003**, *108*, 4407. [CrossRef]
5. Caesar, L.; Rahmstorf, S.; Robinson, A.; Feulner, G.; Saba, V. Observed fingerprints of weakening Atlantic Ocean overturning circulation. *Nature* **2018**, *556*, 191–196. [CrossRef]
6. Cook, E.R.; Kushnir, Y.; Smerdon, J.E.; Williams, A.P.; Anchukaitis, K.J.; Wahl., E.R. A Euro-Mediterranean tree-ring reconstruction of the winter NAO index since 910CE. *Clim. Dyn.* **2019**, *53*, 1567–1580. [CrossRef]
7. Luterbacher, J.; Xoplaki, E.; Dietrich, D.; Rickli, R.; Jacobeit, J.; Beck, C.; Gyalistras, D.; Schmutz, C.; Wanner, H. Reconstruction of sea level pressure fields over the Eastern North Atlantic and Europe back to 1500. *Clim. Dyn.* **2002**, *18*, 545–561. [CrossRef]
8. Gray, S.T.; Graumlich, L.J.; Betancourt, J.L.; Pederson, G.T. A tree-ring based reconstruction of the Atlantic Multidecadal Oscillation since 1567 AD. *Geophys. Res. Lett.* **2004**, *31*, L12205. [CrossRef]
9. Knight, J.R.; Allan, R.J.; Folland, C.K.; Vellinga, M.; Mann, M.E. A signature of persistent natural thermohaline circulation cycles in observed climate. *Geophys. Res. Lett.* **2005**, *32*, L20708. [CrossRef]
10. Baker, A.; Hellstrom, J.C.; Kelly, B.F.J.; Mariethoz, G.; Trouet, V. A composite annual-resolution stalagmite record of North Atlantic climate over the last three millennia. *Sci. Rep.* **2015**, *5*, 10307. [CrossRef]
11. Woollings, T.; Franzke, C.; Hodson, D.L.R.; Dong, B.; Barnes, E.A.; Raible, C.C.; Pinto, J.G. Contrasting interannual and multidecadal NAO variability. *Clim. Dyn.* **2015**, *45*, 539–556. [CrossRef]
12. Seip, K.L.; Gron, O. Atmospheric and Ocean Dynamics May Explain Cycles in Oceanic Oscillations. *Climate* **2019**, *7*, 77. [CrossRef]
13. Privalsky, V.; Yushkov, V. Getting It Right Matters: Climate Spectra and Their Estimation. *Pure Appl. Geophys.* **2018**, *175*, 3085–3096.
14. Mann, M.E.; Steinman, B.A.; Miller, S.K. Absence of internal multidecadal and interdecadal oscillations in climate model simulations. *Nat. Commun.* **2020**, *11*, 1–9. [CrossRef] [PubMed]
15. Seip, K.L.; Grøn, Ø.; Wang, H. The North Atlantic oscillations: cycle times for the NAO, the AMO and the AMOC. *Climate* **2019**, *7*, 43. [CrossRef]
16. Seip, K.L.; Grøn, Ø. On the statistical nature of distinct cycles in global warming variables. *Clim. Dyn.* **2019**, *52*, 7329–7337. [CrossRef]
17. Mazzarella, A.; Scafetta, N. Evidences for a quasi 60-year North Atlantic Oscillation since 1700 and its meaning for global climate change. *Theor. Appl. Climatol.* **2012**, *107*, 599–609. [CrossRef]
18. Delworth, T.L.; Zeng, F.; Zhang, L.; Vecchi, G.A.; Yang, X.; Zhang, R. The Central Role of Ocean Dynamics in Connecting the North Atlantic Oscillation to the Extratropical Component of the Atlantic Multidecadal Oscillation. *J. Clim.* **2017**, *30*, 3789–3805. [CrossRef]
19. Wu, T.W.; Hu, A.; Gao, F.; Zhang, J.; Meehl, G.A. New insights into natural variability and anthropogenic forcing of global/regional climate evolution. *Npj Clim. Atmos. Sci.* **2019**, *2*, 18. [CrossRef]
20. Haskins, R.K.; Oliver, K.I.C.; Jackson, L.C.; Wood, R.A.; Drijfhout, S.S. Temperature domination of AMOC weakening due to freshwater hosing in two GCMs. *Clim. Dyn.* **2019**, *54*, 273–286.
21. Imbrie, J.; Berger, A.; Boyle, E.A.; Clemens, S.C.; Duffy, A.; Howard, W.R.; Kukla, G.; Kutzbach, J.; Martinson, D.G.; Mcintyre, A.; et al. On the Structure and Origin of Major Glaciation Cycles 2. The 100,000-Year Cycle. *Paleoceanography* **1993**, *8*, 699–735. [CrossRef]

22. Li, S.J.; Wu, L.X.; Yang, Y.; Geng, T.; Cai, W.J.; Gan, B.L.; Chen, Z.H.; Jing, Z.; Wang, G.J.; Ma, X.H. The Pacific Decadal Oscillation less predictable under greenhouse warming. *Nat. Clim. Chang.* **2020**, *10*, 30–34. [CrossRef]
23. Little, C.M.; Hu, A.X.; Hughes, C.W.; McCarthy, G.D.; Piecuch, C.G.; Ponte, R.M.; Thomas, M.D. The Relationship Between US East Coast Sea Level and the Atlantic Meridional Overturning Circulation: A Review. *J. Geophys. Res. Oceans* **2019**, *124*, 6435–6458. [CrossRef] [PubMed]
24. Kestin, T.S.; Karoly, D.J.; Yang, J.I.; Rayner, N.A. Time-frequency variability of ENSO and stochastic simulations. *J. Clim.* **1998**, *11*, 2258–2272. [CrossRef]
25. Clement, A.; Bellomo, K.; Murphy, L.N.; Cane, M.A.; Mauritsen, T.; Radel, G.; Stevens, B. The Atlantic Multidecadal Oscillation without a role for ocean circulation. *Science* **2015**, *350*, 320–324.
26. Chen, H.G.; Shen, J.Y.; Chen, W.H.; Wu, C.Y.; Huang, C.S.; Yi, Y.Y.; Qian, J.C. The Bivariate Empirical Mode Decomposition and Its Contribution to Grinding Chatter Detection. *Appl. Sci.* **2017**, *7*, 145. [CrossRef]
27. Wang, L.; Ting, M.; Kushner, P.J. A robust empirical seasonal prediction of winter NAO and surface climate. *Sci. Rep.* **2017**, *7*, 279. [CrossRef]
28. Hurrell, J.W. Decadal Trends in the North-Atlantic Oscillation—Regional Temperatures and Precipitation. *Science* **1995**, *269*, 676–679. [CrossRef]
29. Hurrell, J.W.; Deser, C. North Atlantic climate variability: The role of the North Atlantic Oscillation. *J. Mar. Syst.* **2010**, *79*, 231–244. [CrossRef]
30. Birkel, S.D.; Mayewski, P.A.; Maasch, K.A.; Kurbatov, A.V.; Lyon, B. Evidence for a volcanic underpinning of the Atlantic multidecadal oscillation. *Npj Clim. Atmos. Sci.* **2018**, *1*, 1–7. [CrossRef]
31. Tatli, H.; Menteş, Ş.S. Detrended cross-correlation patterns between North Atlantic oscillation and precipitation. *Theor. Appl. Climatol.* **2019**, *138*, 387–397. [CrossRef]
32. Mosedale, T.J.; Stephenson, D.B.; Collins, M.; Mills, T.C. Granger causality of coupled climate processes: Ocean feedback on the North Atlantic oscillation. *J. Clim.* **2006**, *19*, 1182–1194. [CrossRef]
33. Seip, K.L.; McNown, R. The timing and accuracy of leading and lagging business cycle indicators: a new approach. *Int. J. Forecast.* **2007**, *22*, 277–287. [CrossRef]
34. Seip, K.L.; Grøn, Ø. Cycles in oceanic teleconnections and global temperature change. *Theor. Appl. Climatol.* **2018**, *136*, 985–1000. [CrossRef]
35. Robson, J.; Ortega, P.; Sutton, R. A reversal of climatic trends in the North Atlantic since 2005. *Nat. Geosci.* **2016**, *9*, 513–517. [CrossRef]
36. Watson, A.J.; Schuster, U.; Bakker, D.C.E.; Bates, N.R.; Corbiere, A.; Gonzalez-Devila, M.; Friedrich, T.; Hauck, J.; Heinze, C.; Johannessen, T.; et al. Tracking the Variable North Atlantic Sink for Atmospheric CO2. *Science* **2009**, *326*, 1391–1393. [CrossRef]
37. Guallart, E.F.; Schuster, U.; Fajar, N.M.; Legge, O.; Brown, P.; Pelejero, C.; Messias, M.J.; Calvo, E.; Watson, A.; Rios, A.F.; et al. Trends in anthropogenic CO2 in water masses of the Subtropical North Atlantic Ocean. *Prog. Oceanogr.* **2015**, *131*, 21–32. [CrossRef]
38. Thomas, H.; Prowe, A.E.F.; Lima, I.D.; Doney, S.C.; Wanninkhof, R.; Greatbatch, R.J.; Schuster, U.; Corbiere, A. Changes in the North Atlantic Oscillation influence CO2 uptake in the North Atlantic over the past 2 decades. *Glob. Biogeochem. Cycles* **2008**, *22*, GB4027. [CrossRef]
39. Gruber, N.; Clement, D.; Carter, B.R.; Feely, R.A.; van Heuven, S.; Hoppema, M.; Ishii, M.; Key, R.M.; Kozyr, A.; Lauvset, S.K.; et al. The oceanic sink for anthropogenic CO2 from 1994 to 2007. *Science* **2019**, *363*, 1193–1199.
40. Landschutzer, P.; Gruber, N.; Bakker, D.C.E. Decadal variations and trends of the global ocean carbon sink. *Glob. Biogeochem. Cycles* **2016**, *30*, 1396–1417.
41. Goris, N.; Tjiputra, J.F.; Olsen, A.; Schwinger, J.; Lauvset, S.K.; Jeansson, E. Constraining Projection-Based Estimates of the Future North Atlantic Carbon Uptake. *J. Clim.* **2018**, *31*, 3959–3978. [CrossRef]
42. Khatiwala, S.; Schmittner, A.; Muglia, J. Air-sea disequilibrium enhances ocean carbon storage during glacial periods. *Sci. Adv.* **2019**, *5*, eaaw4981. [CrossRef] [PubMed]
43. Sutton, R.T.; Hodson, D.L.R. Atlantic Ocean forcing of North American and European summer climate. *Science* **2005**, *309*, 115–118. [CrossRef] [PubMed]
44. Ghosh, R.; Muller, W.A.; Baehr, J.; Bader, J. Impact of observed North Atlantic multidecadal variations to European summer climate: a linear baroclinic response to surface heating. *Clim. Dyn.* **2017**, *48*, 3547–3563. [CrossRef]

45. Rousi, E.; Rust, H.W.; Ulbrich, U.; Anagnostopoulou, C. Implications of Winter NAO Flavors on Present and Future European Climate. *Climate* **2020**, *8*, 13. [CrossRef]
46. Chen, X.Y.; Tung, K.K. Global surface warming enhanced by weak Atlantic overturning circulation. *Nature* **2018**, *559*, 387–391. [CrossRef]
47. Wei, M.; Qiao, F.; Guo, Y.; Deng, J.; Song, Z.; Shu, Q.; Yang, X. Quantifying the importance of interannual, interdecadal and multidecadal climate natural variabilities in the modulation of global warming rates. *Clim. Dyn.* **2019**, *53*, 6715–6727.
48. Hughes, K.M.; Dransfeld, L.; Johnson, M.P. Climate and stock influences on the spread and locations of catches in the northeast Atlantic mackerel fishery. *Fish. Oceanogr.* **2015**, *24*, 540–552. [CrossRef]
49. Faillettaz, R.; Beaugrand, G.; Goberville, E.; Kirby, R.R. Atlantic Multidecadal Oscillations drive the basin-scale distribution of Atlantic bluefin tuna. *Sci. Adv.* **2019**, *5*, 8. [CrossRef]
50. Beaugrand, G.; Reid, P.C. Relationships between North Atlantic salmon, plankton, and hydroclimatic change in the Northeast Atlantic. *Ices J. Mar. Sci.* **2012**, *69*, 1549–1562. [CrossRef]
51. Drinkwater, K.F.; Kristiansen, T. A synthesis of the ecosystem responses to the late 20th century cold period in the northern North Atlantic. *Ices J. Mar. Sci.* **2018**, *75*, 2325–2341. [CrossRef]
52. Behrenfeld, M.J.; O'Malley, R.T.; Siegel, D.A.; McClain, C.R.; Sarmiento, J.L.; Feldman, G.C.; Milligan, A.J.; Falkowski, P.G.; Letelier, R.M.; Boss, E.S. Climate-driven trends in contemporary ocean productivity. *Nature* **2006**, *444*, 752–755.
53. Cushing, D.H. Plankton Production and Year-Class Strength in Fish Populations—An Update of the Match Mismatch Hypothesis. *Adv. Mar. Biol.* **1990**, *26*, 249–293.
54. Tømte, O.; Seip, K.L.; Christophersen, N. Evidence That Loss in Predictability Increases with Weakening of (Metabolic) Links to Physical Forcing Functions in Aquatic Ecosystems. *Oikos* **1998**, *82*, 325–332. [CrossRef]
55. Sugihara, G.; May, R.; Ye, H.; Hsieh, C.H.; Deyle, E.; Fogarty, M.; Munch, S. Detecting Causality in Complex Ecosystems. *Science* **2012**, *338*, 496–500. [CrossRef] [PubMed]
56. Seip, K.L.; Pleym, H. Competition and predation in a seasonal world. *Verh. Internat. Verein. Limnol.* **2000**, *27*, 823–827. [CrossRef]
57. Seip, K.L. Doers tax reduction have an effect on gross domestic product? An empirical investigation. *J. Policy Model.* **2019**, *41*, 1128–1143. [CrossRef]
58. Knutti, R.; Stocker, T.F.; Joos, F.; Plattner, G.K. Probabilistic climate change projections using neural networks. *Clim. Dyn.* **2003**, *21*, 257–272. [CrossRef]
59. Foster, G.L.; Royer, D.L.; Lunt, D.J. Future climate forcing potentially without precedent in the last 420 million years. *Nat. Commun.* **2017**, *8*, 14845. [CrossRef]
60. Zhang, R.; Delworth, T.L.; Rosati, A.; Anderson, W.G.; Dixon, K.W.; Lee, H.C.; Zeng, F.R. Sensitivity of the North Atlantic Ocean Circulation to an abrupt change in the Nordic Sea overflow in a high resolution global coupled climate model. *J. Geophys. Res. Ocean.* **2011**, *116*, 12024. [CrossRef]
61. Hollis, C.J.; Taylor, K.W.R.; Handley, L.; Pancost, R.D.; Humber, M.; Creech, J.B.; Hines, B.R.; Erica, M.C.A.; Morgans, H.E.G.; Crampton, J.S.; et al. Early Paleogene temperature history of the Southwest Pacific Ocean: Reconciling proxies and models. *Earth Planet. Sci. Lett.* **2012**, *349*, 53–56. [CrossRef]
62. Lunt, D.J.; Elderfield, H.; Pancost, R.; Ridgwell, A.; Foster, G.L.; Haywood, A.; Kiehl, J.; Sagoo, N.; Shields, C.; Stone, E.J.; et al. Warm climates of the past-a lesson for the future? *Philos. Trans. R. Soc. a-Math. Phys. Eng. Sci.* **2013**, *371*, 20130146. [CrossRef] [PubMed]
63. Gastineau, G.; D'Andrea, F.; Frankignoul, C. Atmospheric response to the North Atlantic Ocean variability on seasonal to decadal time scales. *Clim. Dyn.* **2013**, *40*, 2311–2330. [CrossRef]
64. O'Reilly, C.H.; Huber, M.; Woollings, T.; Zanna, L. The signature of low-frequency oceanic forcing in the Atlantic Multidecadal Oscillation. *Geophys. Res. Lett.* **2016**, *43*, 2810–2818. [CrossRef]
65. Trenary, L.; Delsole, T. Does the Atlantic Multidecadal Oscillation Get Its Predictability from the Atlantic Meridional Overturning Circulation? *J. Clim.* **2016**, *29*, 5267–5280. [CrossRef]
66. Cassou, C.; Kushnir, Y.; Hawkins, E.; Pirani, A.; Kucharski, F.; Kang, I.S.; Caltabiano, N. Decadal Climate Variability and Predictability: Challenges and Opportunities. *Bull. Am. Meteorol. Soc.* **2018**, *99*, 479–490. [CrossRef]

67. Zhang, L.P.; Delworth, T.L.; Zeng, F.R. The impact of multidecadal Atlantic meridional overturning circulation variations on the Southern Ocean. *Clim. Dyn.* **2017**, *48*, 2065–2085. [CrossRef]
68. Wu, S.; Liu, Z.Y.; Zhang, R.; Delworth, T.L. On the observed relationship between the Pacific Decadal Oscillation and the Atlantic Multi-decadal Oscillation. *J. Oceanogr.* **2011**, *67*, 27–35. [CrossRef]