
iAtlantic Deliverable 3.3

Risk assessments of future changes to ecosystem dynamics and risk of tipping points

Confidence assessment of the risks posed by future oceanographic changes to iAtlantic ecosystems

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List of Acronyms

AAIW	Antarctic Intermediate Water
ABMTs	Area-Based Management Tools
AMO	Atlantic Multi-Decadal Oscillation
AMOC	Atlantic Meridional Overturning Circulation
BATS	Bermuda Atlantic Time-Series Study
CDW	Circumpolar Deep Water
CMIP	Coupled Model Intercomparison Projects
EAF	Ecosystem Approach to Fisheries
EIA	Environmental Impact Assessment
ENACW	Eastern North Atlantic Central Water
EOVs	Essential Ocean Variables
FOCI	Flexible Ocean and Climate Infrastructure
GOOS	Global Ocean Observing System
ICCAT	International Commission for the Conservation of Atlantic Tunas
MSP	Marine Spatial Planning
NADW	North Atlantic Deep Water
NEABW	Northeast Atlantic Bottom Water
NPP	Net Primary Production
OECMs	Other Effective Area-Based Conservation Measures
S	Absolute Salinity
SACW	South Atlantic Central Water
SEA	Strategic Environmental Assessment
SSP5	Shared Socioeconomic Pathway 5
SST	Sea Surface Temperature
STUW	Subtropical Under Water
T	Seawater Temperature
TAC	Total Allowable Catch
VME	Vulnerable Marine Ecosystem
WNACW	Western North Atlantic Central Water
WP	Work Package
WSACW	Western South Atlantic Central Water

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Executive Summary

Deliverable 3.3 is an assessment of how confident iAtlantic's time series analysts are that future ocean conditions forecasted by Work Package (WP) 1 will impact the ecosystem compartments we studied in WP 3. This brings together the future ocean changes predicted in *Deliverable 1.2* with how sensitive ecosystem compartments were to those variables in the past using results presented in *Deliverable 3.2*. First, the approach semi-quantitatively scored the 'Likelihood' of a significant change happening in three Essential Ocean Variables (EOVs) by 2070. This was based on forecasts for all 12 Study Regions and included Atlantic Meridional Overturning Circulation strength (AMOC), conservative seawater temperature (T), and absolute salinity (S). Second, the approach semi-quantitatively scored the 'Consequences' of those changes for the ecosystem compartments studied in *Deliverable 3.2*. After careful integration across defined water masses and EOVs, a combined score for each Study Region was obtained. Higher scores indicated more confidence that forecasted changes would bring about ecosystem changes by 2070.

Summary Assessment Reports were produced for each Study Region. These overwhelmingly showed high confidence that future sea temperatures are going to have consequences for the ecosystem compartments that we studied in WP 3. Moderate to high scores due to temperature change were identified in 9 out of 12 Study Regions. When averaged across all 3 EOVs, we have the highest confidence that the ecosystems we studied around Iceland (capelin, groundfish including monkfish, humpbacks) and in the Malvinas Current (cold-water coral mounds, billfish, tuna, and pelagic sharks) are going to change by 2070. We do not imply whether an ecosystem change leads to positive or negative outcomes, just that the delivery of ecosystem services arising from those ecosystem compartments is likely to change, which should put managers and their authorities on alert. For Study Regions and ecosystems where we were less confident about ecosystem change, our approach presents a simple integrated assessment framework to update these scores once more ecosystem time series are added or new analyses of their drivers of change become available.

Our semi-quantitative assessments provide the opportunity for managers to reflect on how to integrate ecosystem changes into their own decision-making powers at local, regional and international levels through a series of recommendations:

- ✓ ramp up investments in monitoring and mitigating change in certain regions, especially at high latitudes where we are confident that multiple ecosystem compartments will change by 2070;
- ✓ ensure adequate investment and resourcing to collect and share ocean observations across the Atlantic, particularly in Study Regions where ocean temperatures are likely to warm and where a marine 'tropicalisation' has already been apparent the last two decades;
- ✓ build and maintain public-private partnerships, industry collaborations, and data-sharing mechanisms across diverse knowledge systems to enable similar or repeat assessments;
- ✓ deliver on commitments to slow the pace of global climate change, and use a portfolio of ABMTs to increase resilience.

Caveats and uncertainties in both oceanographic and ecosystems inputs to iAtlantic's semi-quantitative assessments were reported in *Deliverables 1.2* and *3.2*, but the present assessment still provides decision-makers with a better place-based understanding of whether future oceanographic conditions could alter living marine resources important to the Atlantic socioeconomy. Should human activities continue at current rates and blue growth be permitted in regions scored at 'High confidence' then impacts of additional human activities could further compound these changes and push or 'tip' ecosystems into alternate states or regimes that may be less desirable. To avoid this, managers and their authorities need to develop policies to ensure effective monitoring and mitigation measures can be implemented to maintain ecosystem function.

Introduction

Sustainable ocean management that balances resource exploitation with protection requires us to have a better understanding of the pace at which climate change is expected to impact marine ecosystems in the deep and open ocean. Current understanding is that the ‘velocity’ of such change will greatly accelerate over the next century with the rate of change in water temperature expected to profoundly affect species and ecosystems, particularly at mid-ocean depths 200–1,000 m below the surface (Brito-Morales et al. 2020).

Cumulative impacts of multiple stressors from climate change and human activities affect an ecosystem’s stability and its resilience to perturbations. Consequences could be severe for some regions and local communities dependent on sectors like offshore fisheries but also for communities dependent on marine wildlife tourism where the targets are wide-ranging or highly migratory species. For Atlantic nations, economic, human well-being, and national security issues are all closely tied to the status of the marine environment, the resources it provides, and the impacts of climate change (Hall and Webber 2022). Managers and their authorities need to understand the risks associated with compounding multiple stressors. They could respond by taking substantive actions, e.g., considering climate change in commercial fish stock assessments, advocating for measures that confer climate change resilience, or adapting governance (Pinsky et al. 2018; Sumbly et al. 2021).

Modelling frameworks to forecast ocean conditions and the biological/ecosystem response, and the corresponding quantification of any uncertainties, are useful tools to understand where and when changes to marine resources are likely to occur. The iAtlantic project takes modelling frameworks combined with empirical and experimental approaches to predict the future ocean (Work Package (WP) 1), understand spatial drivers of species distributions (WP 2), and impacts of multiple stressors on marine species and ecosystems (WP 4).

The main goal of WP 3 was to understand historical drivers of change and tipping points. To make even more use of the results in *Deliverable 3.2*, WP 3 also explored a new method to use its analyses of past drivers of change and tipping points to explore the impacts that future oceanographic changes could have on the ecosystems we studied. Broadly taking inspiration from the Food and Agriculture Organization of the United Nations’ Ecosystem Approach to Fisheries (EAF) planning and implementation tools, *Deliverable 3.3* presents a semi-quantitative assessment of how certain we are that these ocean forecasts will have consequences for the ecosystems we studied in WP 3. This presumes that if an ocean variable was found to have been an important driver to an ecosystem compartment (e.g., zooplankton, bacteria, whales) in the past, then future changes in that variable will continue to have consequences for that compartment.

A similar approach to such assessments was adopted by the FP7 PERSEUS project (‘Policy-oriented marine environmental research in the Southern European Seas’, Grant Agreement No. 287600) for their adaptive management toolbox. In iAtlantic, this approach to assessments can highlight where investments in infrastructure, human resources and capacity in general could be ramped up to support planning decisions and identify oceanographic parameters and ecosystem compartments to monitor.

Notably, it is also a formalised system that enables such assessments where insufficient information otherwise prevents more quantitative methods. It requires creating a way to score ‘Consequences’ (how certain we are based on *Deliverable 3.2* that an ecosystem compartment was sensitive and responds to changes in an ocean variable over the past, and the ‘Likelihood’ that the values of these ocean variables are going to change in the future using predictions made in *Deliverable*

1.2. Thus, our confidence in how likely future oceanographic changes are going to impact our deep and open ocean ecosystems can be derived as a product of Consequence x Likelihood; the higher the score, the more confident we are that ecosystems in a Study Region are going to change as a result of oceanographic changes.

The iAtlantic approach

The Global Ocean Observing System (GOOS) formed a series of expert panels to agree a suite of Essential Ocean Variables (EOVs) based on their relevance, feasibility, and cost-effectiveness (Miloslavich et al. 2017). Sea temperature, salinity and ocean currents are all included as EOVs as these were considered critical to understanding linkages between ocean circulation and the distribution of and transport of heat and salt in the world's oceans. Oceanographic forecasts of future ocean temperatures (T), salinities (S), and strength of the Atlantic Meridional Overturning Circulation (AMOC) were performed by iAtlantic WP 1 (see *Deliverable 1.2*). The ocean generalised circulation models were challenged by some Study Regions having complex circulation patterns that also vary spatially and temporally and, in some cases, water masses identified by *in situ* observational data might not have been adequately represented by forecast model output. In parallel, analysis of ecosystem time series in iAtlantic WP 3 were also challenged by, e.g., noisy data, incomplete or short time series, and in some cases quite high levels of uncertainty in terms of environmental drivers.












Our assessments of how certain we are that future ocean conditions will be accompanied by ecosystem changes still come with all the caveats and uncertainties already reported in *Deliverables 1.2* and *3.2*. However, the assessments still provide decision-makers with precautionary information and an improved place-based understanding of whether future oceanographic conditions could alter living marine resources, many of which are critical to the Atlantic socioeconomy. Fully integrating climate change into ocean planning instruments (e.g., marine spatial planning, strategic environmental assessment, environmental assessment) must consider shifting baselines alongside human activities to assess and mitigate impacts as we strive to achieve sustainable development.

Should blue growth activities be permitted in Study Regions scored at 'High confidence' without effective mitigation and monitoring, then impacts of additional human activities could further compound these changes and tip these ecosystems into less desirable states or conditions. The purpose of this Deliverable is to identify which Study Regions analysed in *Deliverable 3.2* we have high confidence are going to be significantly altered by combined effects of changes to ocean circulation, temperature or salinity by 2070.

Methodology

Work package 3 examined drivers of change and ecosystem tipping points in each of iAtlantic's 12 Study Regions. The time series available for analysis differed between Study Regions, both in spatial and temporal extent (see *Deliverables 3.1* and *3.2*), but also in terms of which ecosystem compartments ([Table 1](#)) had datasets available to iAtlantic. These ranged from bacterioplankton to the great whales.

Table 1: Range of ecosystem compartments and time series datasets analysed in WP 3.

Ecosystem compartment	Description of time series datasets
	geochemical reconstructions solely using diatoms, coccolithophores and/or foraminiferans
	geochemical reconstructions using cold-water corals and coral mounds
	bacterioplankton
	phytoplankton including pico- and nanoeukaryotes
	zooplankton
	benthic microbes
	benthic invertebrates
	demersal fish, crustaceans and squid
	smaller pelagic fish
	tuna, billfish, oceanic sharks
	cetaceans

For each ecosystem time series analysed (ecological, geological and using palaeoproxies) we scored:

- the *Likelihood* of oceanographic changes, referring to whether AMOC, temperature, or salinity were forecasted to decrease or increase between the present day and 2070 within the approximate water mass and depth range of where each time series was obtained;
- and
- the *Consequences* of change, referring to whether any strong or statistically significant effects, shifts, or tipping points/breakpoints in ecosystem compartments were found to be driven by ocean circulation (AMOC), sea temperature, and salinity according to results presented in *Deliverable 3.2*. To help the reader, a worked example of how Consequences were calculated is provided in Supplementary Material 1, using the zooplankton time series from Study Region 4 as an example.

Assessing the Future Ocean ('Likelihood')

Forecast simulations of conservative T, absolute S (from here on, simply T and S), and AMOC were produced using the Flexible Ocean and Climate Infrastructure Version 1 (FOCI; Matthes et al. 2020) by WP 1 and (see *Deliverable 1.2*). Briefly, two types of observational data were used to define water

masses. First, these included estimates of AMOC from *in situ* moored observing systems around the Atlantic Ocean: OSNAP (57°N), RAPID (26°N), TRACOS (11°S), and SAMOC (34.5°S). AMOC strength was defined as the maximum of the meridional overturning stream function below 500 m water depth at the latitudes of the observational time series listed above. Second, EN4 observational data of the water column including ship-based and Argo floats profiling of T-S were also used. A series of T-S diagrams were created for each of the 12 Study Regions, and used along with source water types (Liu and Tanhua 2021) to identify water masses in each region. In this way, water masses were defined for each Study Region that accounted for changes in density as a water mass moves away from its source region. Note however, that defining water masses at the sea surface is not straightforward because T and S properties change continuously through interactions with the atmosphere. After water leaves the well-mixed surface layer and enters the ocean interior, water mass can be reliably tracked using its T and S (or density) with T and S still changing through mixing, but much more slowly than at the sea surface. Thus, forecasts from the sea surface to at least 50 m water depth are not represented in Study Regions other than in Study Region 6 and 7, but water masses deeper down are always captured.

All simulation experiments of future ocean conditions in each water mass layer followed the Coupled Model Intercomparison Projects (CMIP) Shared Socioeconomic Pathway 5 (SSP5-8.5) climate model for a high emission future scenario (Meinhausen et al. 2017); i.e., a worst case scenario. The FOCI outputs used to conduct assessments for this Deliverable are presented in Appendix B (for AMOC) and Appendix F (for conservative T and absolute S) in *Deliverable 1.2* for reference and are not reported again in this Deliverable. The appendices in *Deliverable 1.2* report the significance of the forecasted changes in ensemble FOCI models of AMOC, T, and S at 95% confidence intervals and the trend (Sv/decade, °C/decade, and g·kg⁻¹/decade, respectively) for each water mass and Study Region.

For each variable (future AMOC strength, T, S), the Likelihood of change was scored as *Very Likely* (score = 3), *Possible* (score = 2), *Unlikely* (score = 1), or *Not Assessed* (score = 0) according to the ensemble model products. *Very Likely* refers to significant changes in that variable; *Possible* refers to change but this was not significant; *Unlikely* refers to no changes forecasted. *Not Assessed* refers to when a water mass was not easily identifiable in the T-S diagrams for the FOCI runs in a particular Study Region, and thus forecast runs could not be created due the lower spatial resolution of the FOCI model.

Assessing severity of impacts on marine ecosystems ('Consequences')

Similar to the scoring system developed for 'Likelihood', the 'Consequences' of ecosystem compartment change were scored according to the outcomes of statistical tests but with some integration of expert judgement as needed.

For Consequences, we scored these as being either *Major Changes* (score = 3), *Minor Changes* (score = 2), *Inconclusive* (score = 1), or *Not Assessed* (score = 0).

Major Changes specifically refer to outcomes reported in *Deliverable 3.2* wherein expert analyses demonstrated strong and statistically significant effects, shifts, or tipping/break points related to ocean circulation, sea temperature or salinity. Thus in this case, experts have higher confidence that an ocean variable is an important driver of change to that ecosystem compartment, and therefore that future changes to that variable will continue to be an important driver of ecosystem change.

Minor changes refers to outcomes reported in *Deliverable 3.2* that detected some effects, shifts or tipping points relating to the environmental variables but these trends were not reported by the experts as being particularly strong or they were not statistically significant. Minor changes also referred to situations where experts concluded that there could be a relationship between an ecosystem compartment and the oceanographic variable, but that this relationship was probably coincident with

other unmeasured variables, rather than the variable itself. Thus in this case, experts have less confidence that an ocean variable is an important driver of change to that ecosystem compartment; therefore, it's less certain that future changes to that variable will cause future ecosystem change.

Inconclusive refers to outcomes of analyses conducted in *Deliverable 3.2* where no clear trend between an ecosystem compartment and an oceanographic variable was found, but where experts still judged that AMOC, T and/or S are still potentially important drivers of change for that compartment. In these cases, it may have been that the time series were just not long enough, or perhaps there was simply too much 'noise' in the ecosystem datasets. Thus in the case of an *Inconclusive* score, experts had weak confidence from their analyses in *Deliverable 3.2* that an ocean variable was an important driver of change to that ecosystem compartment and therefore it's very uncertain whether future changes to that variable will cause any future ecosystem change.

Not Assessed refers to ecosystem time series where relationships between circulation, temperature and salinity were not directly quantified or not considered appropriate for an ecosystem compartment. Because this category yields a score of 0, we provide some further rationale and how this affects our confidence in how important drivers are in our different ecosystem compartments.

Expert judgement was applied in each Study Region to guide the selection of variables to include in analyses for *Deliverable 3.2*. All analysts were encouraged to try at a minimum the variables of AMOC, T, and S. However, some analysts deemed that any possible relationships between our three focal variables and an ecosystem compartment would be spurious at best and not truly indicate a real relationship. For example, time series of benthic communities at the Porcupine Abyssal Plain (Study Region 2) have been studied for nearly three decades and experts judged the roles of the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation to exert far more direct influences on the abyssal ecosystems in this region than AMOC. In this way, scoring 'Consequences' was based on statistical analyses and expert judgement using *Deliverable 3.2*. Post hoc tests for the Nova Scotia slope and Sargasso Sea (Study Regions 4 and 5, respectively) using AMOC strengths were run to further justify the use of expert judgement here, with both cases illustrating the lack of effects or clear patterns when forcing a variable into the tests that experts had already judged would lead to spurious results (see Supplementary Material 2). Thus, in the case of a *Not Assessed* score, experts had no confidence in being able to conclude that an ocean variable was an important driver of change to that ecosystem compartment. Therefore, there is no certainty about whether future changes to that variable will cause any future ecosystem change and likely there is no direct relationship to being with, even if that variable changes in the future.

Integrating Likelihood and Consequences Across Water Masses

Within a Study Region, time series of the ecosystem compartments sometimes came from different water masses, e.g., plankton samples. This did not present an issue for assessing the Likelihood of change for AMOC, because the ensemble forecasts for AMOC at the latitudes of OSNAP, RAPID, TRACOS and SAMOC were defined just as the maximum of the meridional overturning stream function below 500 m water depth. But because each water mass in a Study Region had its own forecast of conservative T and absolute S, each ecosystem time series had to be matched as near as possible to its corresponding water mass using the depth range at which the ecosystem time series was collected or observed (Appendix I). Thus, FOCI outputs for trends in T and S sometimes looked very different between water masses, for example, between the shallowest and the deepest layers in the same Study Region ([Figure 1](#)).

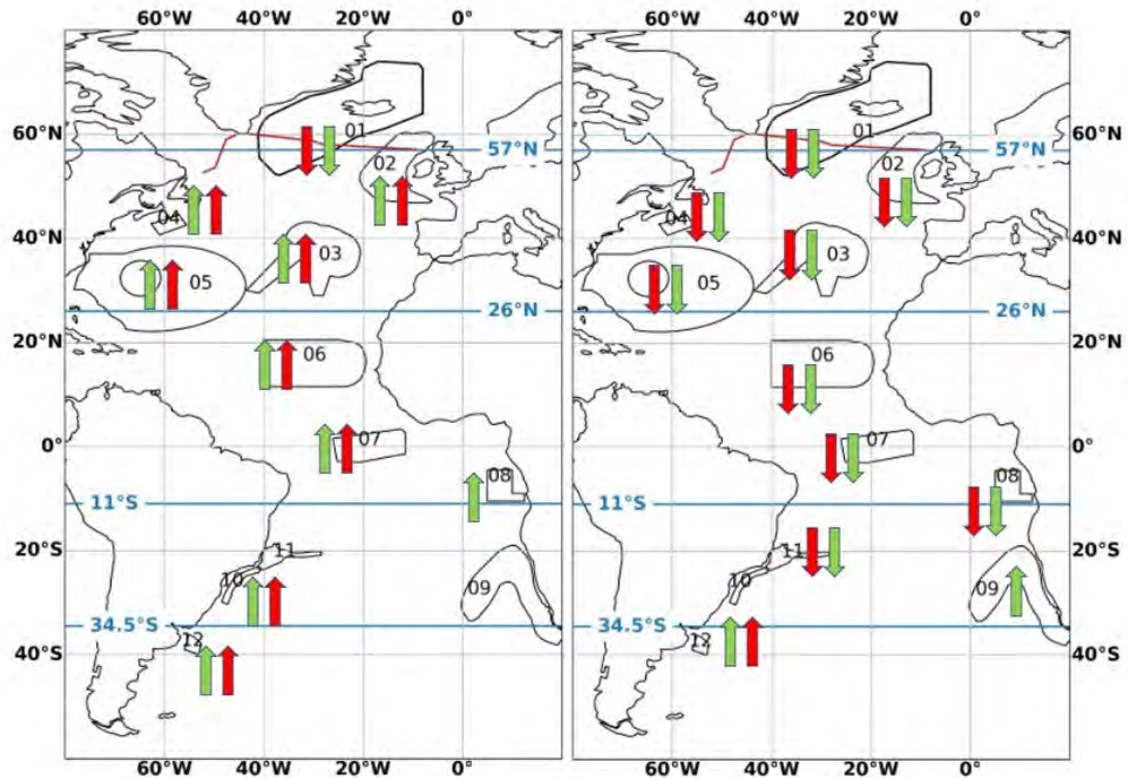


Figure 1: Forecasted trends of temperature (red arrows) and salinity (green arrows) in the shallowest (left) and deepest (right) water mass layers examined for *Deliverable 1.2* in the 12 Study Regions. Direction of arrow indicates the trend (increasing or decreasing); missing arrows indicate a non-significant trend. The shallowest layers are generally forecasted to warm and become more saline, in contrast to the deepest water masses; also note the lack of strong significant trends forecasted in the southeastern Atlantic.

To integrate these trends for an ecosystem time series that was sampled across different water masses (e.g. zooplankton), an average Likelihood of change score was derived that took the mean Likelihood of change score averaged across all the water masses covered by that time series.

After integrating across water masses when needed, a total of 3 Likelihood scores were given, i.e., one for AMOC, one for T, and one for S for each ecosystem compartment in each Study Region. Note, original scores are preserved (Appendix I) if in future a particular layer was of interest to a user and needed to be the focal point.

Calculating an Overall Score for a Study Region

The approach of using Consequences X Likelihood (C-L) produced 3 types of scores for each Study Region: (1) scores listed by ecosystem compartment for each of AMOC, T, and S; (2) scores for AMOC, T, and S for that Study Region overall; and (3) a combined score for that Study Region averaged across risks posed by AMOC, T, and S.

(1) Scores by each ecosystem compartment: With the Likelihood scores for AMOC, T, and S, averaged across water masses for each ecosystem compartment in a Study Region, it was possible to multiply each of these 3 scores by its corresponding Consequence score. This generated a score for that ecosystem compartment individually by AMOC, T, and S. This score could be used when a manager or other user is interested in knowing how confident we are that a particular ecosystem compartment we studied, e.g., demersal fish, is going to change as a direct result of future changes in either AMOC, or T, or S in their Study Region.

(2) *Scores for AMOC, T, and S individually*: Taking the average score across all ecosystem compartments in (1), an overall score was calculated individually for AMOC, T, and S. This score might be used when a manager or other user is interested in knowing how confident we are that all of the ecosystem compartments we studied in a Study Region, e.g., demersal fish, zooplankton, cetaceans, are going to change as a direct result of future changes in either AMOC, or T, or S in their Study Region.

(3) *Combined scores for a Study Region*: A combined mean score was calculated, which averaged all 3 scores from (2) for the whole Study Region. This score can be used when a manager or other user is interested in knowing how confident we are that all of the ecosystem compartments we studied in a Study Region, e.g., demersal fish, zooplankton, cetaceans, are going to change as a direct result of multiple future changes in AMOC, T, and S in their Study Region. **This combined score was subsequently used in *Deliverable 3.3* to identify which iAtlantic Study Regions we are most confident are going to experience ecosystem changes as a result of combined effects of changing AMOC, T, and S by 2070.**

Caveat to the Meanings of ‘High’ versus ‘Low’ Confidence

For the Combined Study Region Score, it’s important to highlight caveats to the assessment methodology and assumptions that had to be made.

‘High’ combined scores refer to results where we are confident from that the ecosystems studied in WP 3 will undergo major alterations related to the combined effects of future AMOC strength, T, and S by 2070. Lower combined scores mean we are less confident about whether oceanographic changes are going to drive changes in the ecosystems we studies, with the lowest scores reflecting that we have only inconclusive or even no evidence to suggest these ecosystems will change as a result of changes in AMOC strength, T, and S.

Note that in this sense, ‘Low’ scores do not mean that these ecosystems are at low risk of changing. Instead, it means that based on our results from *Deliverable 3.2*, we have weak to no confidence in making any kind of determination and that could be for many reasons. Given the nature of many of our time series datasets in the deep and open ocean reported in *Deliverable 3.1* (e.g., irregularly or sparsely collected data, highly variable or noisy datasets, other potentially important environmental drivers of change not hindcasted or forecasted in WP 1 such as biogeochemical variables, etc.), *Deliverable 3.3* helps to illustrate where iAtlantic has come to strong consensus about where we have the most confidence in ecosystems changing as a direct result of future changes in AMOC strength, T, and S.

Results

Assessments are presented below as a summary report for each Study Region. The ecosystem compartments analysed in WP 3, and the rationale behind any links to AMOC, T, and S provided in *Deliverable 3.2* are all provided in order to underpin the scores given to each compartment and each variable (AMOC, T, and S), as well as the combined Study Region score overall. References to any regime shifts, breakpoints and possible tipping points are given in red font to further underscore any links to AMOC, T, or S.

Before the summary reports are provided, it helps to set the context by visualising how the individual scores for each variable varied across Study Regions in the Atlantic Ocean. When averaged across all water masses, changes in AMOC and salinity were not forecasted to significantly change by 2070 ([Figure 2](#), left and central panels). However, significant changes in these variables sometimes occurred in individual water masses (Appendix I). Changes in temperature were forecasted to be

widespread across the Atlantic, even after integration over water masses (Figure 2, right panel).

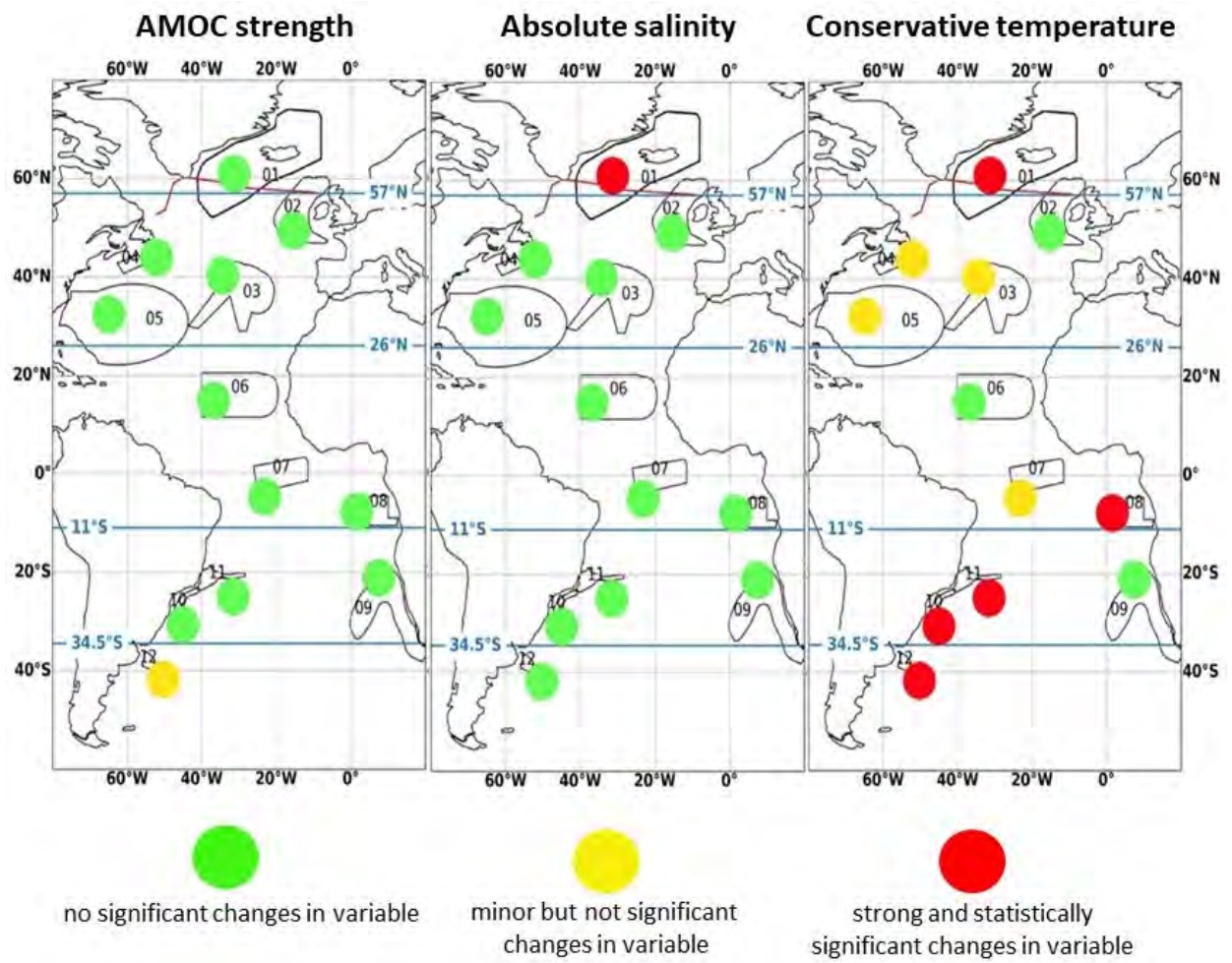






Figure 2: Likelihood of changes to AMOC, S, and T forecasted to occur in the 12 Study Regions by 2070.

Summary Report – Study Region 1, Iceland


Overall, we have high confidence that **future changes in sea temperatures are going to drive changes to deep and open ocean ecosystems around Iceland**, with a mean score for temperature of 8.7 (out of a possible 9). Salinity and AMOC were not often directly assessed so we have lower confidence that these variables drive changes to these ecosystems (mean scores of 6 and 2, respectively).

COMPARTMENTS	ICELAND
	Directly assessed T, S; circulation partly assessed.
	Major shifts in benthic foraminifera communities have been due in part to T over the last 150 years but also possibly linked to changes in salinity and AMOC. There were 2 major industrial era shifts around ~1850 to 1900, and ~1970 (the latter may be linked to increased freshwater in the subarctic Atlantic). Large amplitude decadal variability through the 1990s and early 21 st century was possibly associated with weakening of Labrador Sea Water (LSW) flow in the Deep Western Boundary Current. Recent work suggests density changes in the Labrador Sea could be controlled in part by a weakened AMOC. Underlying mechanisms and circulation patterns associated with these 2 industrial era breakpoints are not fully resolved.
	Total beta diversity index from spring groundfish surveys has been increasing since 2000; in the southwest breakpoints found between 2007 and 2008 and in the northeast, breakpoints were found between 1999 and 2000. A weaker subpolar gyre index was associated with warmer more saline waters driving monkfish range west and north over time but by 2010–2015 this reverted back as waters became less saline; reduced catches of cold water species were noted, e.g., halibut, blue ling and others over the study period.
	Spawning habitat for capelin shifted northwards around 2003 as T warmed and is a possible tipping point, where larval connectivity transported by ocean currents to Greenland was also highest. Connectivity could be reduced if AMOC strength weakens.
	Strong interannual fluctuations coincided with higher cetacean occurrences and these related to strong surface wind stress and lower sea surface salinity (SSS), but June sea surface temperature (SST) <5°C related more to higher humpback whale occurrences.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	foraminifera (T = 3, S = 2, AMOC = 2)
	demersal fisheries (T = 3, S = 1, AMOC = 0)
	monkfish (T = 3, S = 3, AMOC = 0)
	capelin (T = 3, S = 1, AMOC = 3)
	humpbacks (T = 3, S = 3, AMOC = 0)

	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	foraminifera (T = 2.5, S = 3, AMOC = 2)
	demersal fisheries (T = 3, S = 3, AMOC = 2)
	monkfish (T = 3, S = 3, AMOC = 2)
	capelin (T = 3, S = 3, AMOC = 2)
	humpbacks (T = 3, S = 3, AMOC = 2)
	Score for T (Consequence x Likelihood)
	foraminifera = 7.5
	demersal fisheries = 9
	monkfish = 9
	capelin = 9
	humpbacks = 9
	Mean score for T overall = 8.7
	Score for S (Consequence x Likelihood)
	foraminifera = 6
	demersal fisheries = 3
	monkfish = 9
	capelin = 3
	humpbacks = 9
	Mean score for S overall = 6
	Score for AMOC (Consequence x Likelihood)
	foraminifera = 4
	demersal fisheries = 0
	monkfish = 0
	capelin = 6
	humpbacks = 0
	Mean score for AMOC overall = 2
	Combined mean score for T, S, AMOC changes
	foraminifera = 5.83
	demersal fisheries = 4
	monkfish = 6
	capelin = 6
	humpbacks = 6
	Total mean score for Study Region = 5.57



Summary Report – Study Region 2, Porcupine Abyssal Plain

Overall, we have very low confidence that any **future changes in AMOC, T, or S will directly drive changes to the abyssal ecosystem monitored by the EMSO PAP observatory**. AMOC strength and S were not considered likely factors to affect the abyssal fauna here, so were not directly assessed and thus both have mean scores of 0. A mean score for temperature of 3 was given based on possible associations with the Atlantic Multi-decadal Oscillation (AMO), which could alter the ocean thermal regime in the vicinity of the PAP sustained observatory. Other factors affecting the amphipods and megabenthos, such as particle flux and food supply, are expected to far more important in driving temporal patterns, far more so than any changes to AMOC, T, or S.

COMPARTMENTS	PORCUPINE ABYSSAL PLAIN
	S, circulation not directly assessed; T indirectly assessed via Atlantic Multi-decadal Oscillation (AMO).
	Regime shifts were noted in amphipod communities sometime between 1997 and 2011 and were strongly related to AMO state, with obligate necrophages with semelparous reproduction replaced by more iteroparous species like <i>Abyssochomene</i> spp. at higher AMO values. Interannual changes in benthic megafauna were also due to AMO state with peak holothurian abundances (<i>Amperima</i> spp.) from 1996–1999 and 2002 also evidencing regime shifts during AMO transitional states. Both studies were inconclusive about possible roles of AMO due to low power.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	amphipods (T = 1, S = 0, AMOC = 0)
	megabenthos (T = 1, S = 0, AMOC = 0)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	amphipods (T = 3, S = 3, AMOC = 2)
	megabenthos (T = 3, S = 3, AMOC = 2)
	Score for T (Consequence x Likelihood)
	amphipods = 3
	megabenthos = 3
	Mean score for T overall = 3
	Score for S (Consequence x Likelihood)
	amphipods = 0
	megabenthos = 0
	Mean score for S overall = 0
	Score for AMOC (Consequence x Likelihood)
	amphipods = 0
	megabenthos = 0
	Mean score for AMOC overall = 0
	Combined score for T, S, AMOC changes
	amphipods = 1
	megabenthos = 1
	Total mean score for Study Region = 1

Summary Report – Study Region 3, Lucky Strike




Overall, we have medium confidence that **future changes in sea temperatures will drive changes to the Lucky Strike hydrothermal vent ecosystem**, with a mean score for temperature of 4.5 (out of a possible 9). Salinity and AMOC may also play roles, but analysts found only weak or no direct relationships with these variables, so we have far lower confidence that these variables will drive future changes to the microbial mats and mussel assemblages at Lucky Strike (mean scores of 3 and 2, respectively). These species rely on hydrothermal fluids released at the seafloor that create sharp gradients of physico-chemical conditions. Therefore, vent species are less likely to be sensitive to changes in water mass properties. However, the larval life stages of benthic vent species could be at risk and have been investigated in WP 4.

COMPARTMENTS	LUCKY STRIKE
	T, circulation assessed; S not assessed.
	Interannual variability in bacterial mats was very high over the study period at both local and whole-edifice scales, with no obvious periodicity but these mats did seem to grow for longer after 2016. Correlations between bacterial mat coverage S and current direction were not strong or significant, but it was strongly negatively correlated with bottom water T. At the edifice scale, two breakpoints were found between 1995/1999 and 2001 to 2008 when coverage increased, then between 2015 to 2018 and 2018 to 2020 when coverage decreased.
	At the spatial scale of an individual assemblage on the vent, mussel coverage steadily increased until a breakpoint at 2016 after which coverage markedly declined. Coverage was negatively correlated with microbial mat coverage by a lag of 2 months. In contrast, at the scale of the whole edifice, mussel coverage was highly stable. Correlations between mussel coverage and T, S and current direction were never strong or significant. A breakpoint was detected after 2008 when coverage dropped and then recovered by 2015.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	bacterial mats (T = 2, S = 1, AMOC = 1)
	vent mussels (T = 1, S = 1, AMOC = 1)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	bacterial mats (T = 3, S = 3, AMOC = 2)
	vent mussels (T = 3, S = 3, AMOC = 2)
	Score for T (Consequence x Likelihood)
	bacterial mats = 6
	vent mussels = 3
	Mean score for T overall = 4.5
	Score for S (Consequence x Likelihood)
	bacterial mats = 3
	vent mussels = 3

	Mean score for S overall = 3
	Score for AMOC (Consequence x Likelihood)
	bacterial mats = 2
	vent mussels = 2
	Mean score for AMOC overall = 2
	Combined mean score for T, S, AMOC changes
	bacterial mats = 3.67
	vent mussels = 2.67
	Total mean score for Study Region = 3.17

Summary Report – Study Region 4, Scotian Slope, Northwest Atlantic






Overall, we have medium confidence that **future changes in temperature will drive future changes to the deep and open ocean ecosystems over the canyons and other features of the Scotian Slope**, with a mean score for temperature of 4.5 (out of a possible 9) but this is more evident just in the zooplankton time series; relationships between T and demersal fisheries and cetaceans were weaker, thus we have low confidence about these drivers directly causing changes to these ecosystem components as they are likely influenced by a multitude of other factors. AMOC strength was not assessed, and relationships to S were inconclusive (mean scores of 0 and 3, respectively).

COMPARTMENTS	SCOTIAN SLOPE
	T directly assessed, S not directly assessed, circulation not assessed
	Warmer water zooplankton species are becoming more characteristic, which is strongly and significantly related to T. Breakpoints occurred in 2008 (for autumn datasets) and 2014 (for spring datasets). All <i>Calanus hyperboreus</i> life stages are declining in abundance, with breakpoints in 2006 and 2014 (in spring datasets) and in 2010 (in autumn datasets), with significant effects of T but this could relate to timings of spring blooms too. Spring declines are strongly and significantly related to T and chlorophyll a concentration, but autumn declines are inconclusive. T and S have increased between the mixed layer depth and 200 m since 2010.
	Species abundance has decreased over time in shallow strata, e.g., monkfish, witch flounder, and Atlantic halibut. Blackbelly rosefish, sand lance and shortfin squid have become more abundant. Breakpoints occurred at different times across the region: in 1996 and 2012 in shallow strata, and 2004 in the deep strata. The 1995/1996 breakpoint corresponded with a shift from a negative to a positive Atlantic Multi-decadal Oscillation.
	Sightings of long-finned pilot whales and beaked whales in the Gully Marine Protected Area have generally increased over time since 1988, while Atlantic white-sided dolphins and short-beaked common dolphin have decreased. Drivers are likely species-specific and involve multiple biophysical interactions as well as possible effects of underwater noise mitigation measures in the area as opposed to effects of AMOC, T, or S.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	zooplankton (T = 3, S = 2, AMOC = 0)
	<i>Calanus</i> life stages (T = 2, S = 1, AMOC = 0)
	demersal fisheries (T = 1, S = 1, AMOC = 0)
	cetaceans (T = 0, S = 0, AMOC = 0)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	zooplankton (T = 3, S = 3, AMOC = 2)
	<i>Calanus</i> life stages (T = 3, S = 3, AMOC = 2)

	demersal fisheries (T = 3, S = 3, AMOC = 2)
	cetaceans (T = 3, S = 3, AMOC = 2)
	Score for T (Consequence x Likelihood)
	zooplankton = 9
	<i>Calanus</i> life stages = 6
	demersal fisheries = 3
	cetaceans = 0
	Mean score for T overall = 4.5
	Score for S (Consequence x Likelihood)
	zooplankton = 6
	<i>Calanus</i> life stages = 3
	demersal fisheries = 3
	cetaceans = 0
	Mean score for S overall = 3
	Score for AMOC (Consequence x Likelihood)
	zooplankton = 0
	<i>Calanus</i> life stages = 0
	demersal fisheries = 0
	cetaceans = 0
	Mean score for AMOC overall = 0
	Combined score for T, S, AMOC changes
	zooplankton = 5
	<i>Calanus</i> life stages = 3
	demersal fisheries = 2
	cetaceans = 0
	Total mean score for Study Region = 2.5

Summary Report – Study Region 5, Sargasso Sea



Overall, we have medium confidence that **future changes in temperature will drive future changes to the deep and open ocean ecosystems of the Sargasso Sea**, with a mean score for temperature of 4.46 (out of a possible 9). This signal is dominated by strong and significant relationships between temperature on the plankton time series collected for the Bermuda Atlantic Time-series Study (BATS), especially the phytoplankton series. We have much lower confidence that future changes in S and AMOC are going to have consequences for these ecosystems (scores for these were 2.23 and 1.2, respectively), though it was noted that AMOC strength does play a strong and significant effect in controlling the foraminifera and diatoms present at the site.

COMPARTMENTS	SARGASSO SEA
	T, S and circulation assessed (the latter using proxies).
	Diatom productivity and planktic foraminifera abundance indicate large productivity changes and AMOC changes over the Bermuda Rise during the deglacial, which cause major alterations of benthic and pelagic ecosystems.
	Abundances of cyanobacteria have not changed over time and neither have bacterial production rates, but large interannual variability was observed. T is strongly related to <i>Synechococcus</i> spp. (biomass higher in cooler waters) and <i>Prochlorococcus</i> spp. (biomass higher in warmer waters).
	Smaller phytoplankton (pico- and nano-eukaryotes) increased over time, with declines in cryptophytes, diatoms and dinoflagellates, with a major breakpoint in 2004. T is strongly positive and significantly related to prasinophytes in particular. Salinity seems positively related to dinoflagellates, diatoms and cryptophytes. Nutrient and CO ₂ also explain a lot of variability. Primary production has been increasing since 2012.
	Zooplankton abundance and biomass initially increased between 1994 and 2011. Since the 2012 breakpoint, when primary production rates began to increase again, these have decreased and coincide with a return to smaller size fractions that last decade. T, S and other variables explain some of this variability as does phytoplankton biomass composition, so a signal from T and S comes through but this is not strong.
	Estimated abundance increased by nearly one fifth between 2010 and 2020 but there was large interannual variability. Species-specific including behavioural factors, conditions on distant feeding and breeding grounds, and population scale recovery post-whaling have likely contributed to these increases. Notably, primary production also increased since 2012 and this could improve feeding opportunities or encourage whales to stop over longer and increase their sight ability.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)

	foraminifera and diatoms (T = 0, S = 0, AMOC = 3)
	bacterioplankton (T = 3, S = 1, AMOC = 0)
	phytoplankton (T = 3, S = 1, AMOC = 0)
	zooplankton (T = 2, S = 1, AMOC = 0)
	cetaceans (T = 0, S = 1, AMOC = 0)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	foraminifera and diatoms (T = 2.43, S = 2.14, AMOC = 2)
	bacterioplankton (T = 2.43, S = 2.14, AMOC = 2)
	phytoplankton (T = 3, S = 3, AMOC = 2)
	zooplankton (T = 3, S = 3, AMOC = 2)
	cetaceans (T = 3, S = 3, AMOC = 2)
	Score for T (Consequence x Likelihood)
	foraminifera and diatoms = 0
	bacterioplankton = 7.29
	phytoplankton = 9
	zooplankton = 6
	cetaceans = 0
	Mean score for T overall = 4.46
	Score for S (Consequence x Likelihood)
	foraminifera and diatoms = 0
	bacterioplankton = 2.14
	phytoplankton = 3
	zooplankton = 3
	cetaceans = 3
	Mean score for S overall = 2.23
	Score for AMOC (Consequence x Likelihood)
	foraminifera and diatoms = 6
	bacterioplankton = 0
	phytoplankton = 0
	zooplankton = 0
	cetaceans = 0
	Mean score for AMOC overall = 1.2
	Combined mean score for T, S, AMOC changes
	foraminifera and diatoms = 2
	bacterioplankton = 3.14
	phytoplankton = 4
	zooplankton = 3
	cetaceans = 1
	Total mean score for Study Region = 2.63

Summary Report – Study Region 6, Cape Verde

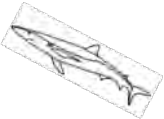
The relatively recent start-up of ecological time series collection around Cape Verde provided insightful new information on seasonal trends in the open ocean ecosystems and particularly the mesoplankton communities at the site. However, the recent start and limited duration of this time series meant that we have extremely low confidence that any **future changes in AMOC, S, or T will directly drive future changes to the open ocean ecosystems around Cape Verde**. This may change in the future when the ecological time series then match longer term oceanographic regime changes around Cape Verde. However, in the meantime, we cannot be confident in concluding anything about how future changes in AMOC strength, T, or S will impact the mesopelagic zooplankton communities analysed in WP 3 (mean scores of 1, 1.07 and 0, respectively) and it's highly likely any changes are also going to be strongly linked instead to changes in trade winds, mesoscale eddies, and net primary productivity regimes.

COMPARTMENTS	CAPE VERDE
	T, S and circulation not directly assessed, but potential roles of T and mesoscale eddy circulation considered.
	Planktic foraminifera illustrate large variability in the productivity regime off Cape Verde. Only preliminary results were available but suggest possible links to sub-Saharan dust export and wind strength.
	Currently, this short time series is characterised by seasonal trends that either obscure or dominate over any interannual trend. Stronger trade winds and upwelling occur over the winter/spring months when aeolian dust export is highest, and zooplankton biomass is positively related to net primary production (NPP), particularly calanoid copepods. The time series may not yet be long enough to have covered significant changes in drivers like mesoscale eddies, trade wind strength, and expansion and intensification of the oxygen minimum zone. However, warming oceans and enhanced stratification are expected to reduce NPP and therefore zooplankton biomass.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	foraminifera (T = 0, S = 0, AMOC = 0)
	zooplankton (T = 1, S = 0, AMOC = 1)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	foraminifera (T = 0, S = 0, AMOC = 2)
	zooplankton (T = 2.4, S = 2.4, AMOC = 2)
	Score for T (Consequence x Likelihood)
	foraminifera = 0
	zooplankton = 2.14
	Mean score for T overall = 1.07

	Score for S (Consequence x Likelihood)
	foraminifera = 0
	zooplankton = 0
	Mean score for S overall = 0
	Score for AMOC (Consequence x Likelihood)
	foraminifera = 0
	zooplankton = 2
	Mean score for AMOC overall = 1
	Combined mean score for T, S, AMOC changes
	foraminifera = 0
	zooplankton = 1.38
	Total mean score for Study Region = 0.69


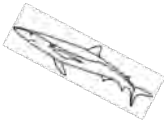
Summary Report – Study Region 7, Romanche Fracture Zone

Overall, we have medium confidence that **future changes in temperature will drive future changes to the open ocean species around the Romanche Fracture Zone in the equatorial Atlantic**, with a mean score for temperature of 4.5 (out of a possible 9). The roles of upwelling cells and circulation in the southeastern Atlantic were indirectly considered, but we have very low confidence at this point that future changes in circulation strength or salinity will have direct impacts on these animals (mean scores of 2 and 0, respectively).

COMPARTMENTS	ROMANCHE FRACTURE ZONE
	T assessed, S and AMOC not assessed but role of upwelling cells considered.
	Analysis of ICCAT species (International Commission for the Conservation of Atlantic Tunas) at the South Atlantic Ocean basin-scale, including most of the Equatorial Fracture Zone showed that the temperature of the catch had increased significantly and constantly since 1978. In the southeast Atlantic, SST got warmer over time, with a 4-year time lag between SST increase and community changes and this effect was strong and significant. Catch biomass used to be characterised and dominated by cooler water species, mostly little tunny, Atlantic bonito, Atlantic bluefin tuna and albacore. But since 2004, catches are characterised by many more species and mostly those with warm water affinities.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	ICCAT species (T = 3, S = 0, AMOC = 1)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	ICCAT species (T = 1.5, S = 1.5, AMOC = 2)
	Score for T (Consequence x Likelihood)
	ICCAT species = 4.5
	Mean score for T overall = 4.5
	Score for S (Consequence x Likelihood)
	ICCAT species = 0
	Mean score for S overall = 0
	Score for AMOC (Consequence x Likelihood)
	ICCAT species = 2
	Mean score for AMOC overall = 2
	Combined mean score for T, S, AMOC changes
	ICCAT species = 2.17
	Total mean score for Study Region = 2.17

Summary Report – Study Region 8, Angola to Congo Lobe

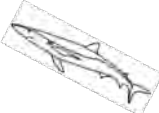
Overall, we have fairly high confidence that **future changes in temperature will directly drive future changes to the deep-sea and open ocean species around Angola and through the Congo Lobe**, with a mean score for temperature of 6.75 (out of a possible 9). Warmer waters were thought to have helped create suitable niches for cold-water corals, while tuna, shark and billfish with warmer water affinities came to dominate catches over time. The roles of changing hydrographic conditions and boundary layers, as well as upwelling cells and circulation in the southeastern Atlantic were indirectly considered, but we still have low confidence at this point that future changes in circulation strength or salinity will directly impact these animals (mean scores of 2 and 3.75, respectively).

COMPARTMENTS	ANGOLA TO CONGO LOBE
	T assessed, S and AMOC assessed for coral mounds but not ICCAT species, though role of upwelling cells considered.
	Warmer more saline thermocline waters and vigorous hydrodynamics at the site were associated with the actual start-up phase of the coral mounds. Coral proliferation was probably more due to vertical shifts in the South Atlantic Central Water (SACW) and Antarctic Intermediate Water (AAIW) boundary layer due to density changes as a result, but also the combination of food and warmer waters creating ideal growth conditions.
	Analysis at the South Atlantic Ocean basin-scale, from off Angola to the Congo Lobe, showed that the temperature of the catch had increased significantly and constantly since 1978. In the southeast Atlantic, sea surface temperature (SST) got warmer over time, with a 4-year time lag between SST increase and community changes and this effect was strong and significant. Catch biomass used to be characterised and dominated by cooler water species, mostly little tunny, Atlantic bonito, Atlantic bluefin tuna and albacore. But since 2004, catches are characterised by many more species and mostly those with warm water affinities.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	ICCAT species (T = 3, S = 0, AMOC = 1)
	coral mounds (T = 3, S = 3, AMOC = 1)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	ICCAT species (T = 2, S = 2.5, AMOC = 2)
	coral mounds (T = 2.5, S = 2.5, AMOC = 2)
	Score for T (Consequence x Likelihood)
	ICCAT species = 6
	coral mounds = 7.5
	Mean score for T overall = 6.75
	Score for S (Consequence x Likelihood)

	ICCAT species = 0
	coral mounds = 7.5
	Mean score for S overall = 3.75
	Score for AMOC (Consequence x Likelihood)
	ICCAT species = 2
	coral mounds = 2
	Mean score for AMOC overall = 2
	Combined mean score for T, S, AMOC changes
	ICCAT species = 2.67
	coral mounds = 5.67
	Total mean score for Study Region = 4.17


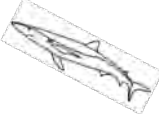
Summary Report – Study Region 9, Walvis Ridge to South Africa

Overall, we have low confidence that **any future changes in AMOC, T, or S will drive changes to oceanic species around the Walvis Ridge to South Africa** (mean scores were 2, 3, and 0, respectively). Tuna, shark, and billfish with warmer water affinities came to dominate catches over time, but sea temperatures for Western South Atlantic Central Water (WSACW) were not forecasted to change at all by 2070 (Appendix F, *Deliverable 1.2*; Appendix I in the present report), making this event unlikely in this water mass where these animals will spend some of their time.

COMPARTMENTS	WALVIS RIDGE TO SOUTH AFRICA
	T assessed, S and AMOC not assessed but role of Aghulas current and upwelling cells considered.
	Analysis at the South Atlantic Ocean basin-scale, from Walvis Ridge to South Africa covering the Benguela Current showed the temperature of the catch had increased significantly and constantly since 1978. In the southeast Atlantic, sea surface temperature (SST) got warmer over time, with a 4-year time lag between SST increase and community changes and this effect was strong and significant. Catch biomass used to be characterised and dominated by cooler water species, mostly little tunny, Atlantic bonito, Atlantic bluefin tuna and albacore. But since 2004, catches are characterised by many more species and mostly those with warm water affinities.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	ICCAT species (T = 3, S = 0, AMOC = 1)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	ICCAT species (T = 1.5, S = 1.5, AMOC = 2)
	Score for T (Consequence x Likelihood)
	ICCAT species = 3
	Mean score for T overall = 3
	Score for S (Consequence x Likelihood)
	ICCAT species = 0
	Mean score for S overall = 0
	Score for AMOC (Consequence x Likelihood)
	ICCAT species = 2
	Mean score for AMOC overall = 2
	Combined mean score for T, S, AMOC changes
	ICCAT species = 1.67
	Total mean score for Study Region = 1.67

Summary Report – Study Region 10, Southeastern Brazil

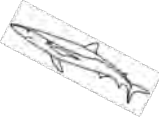
Overall, we have high confidence that **future changes in temperature will drive changes in demersal and oceanic fisheries species in southeastern Brazil** (mean score of 7.5, out of a possible score of 9). Tuna, shark, and billfish with warmer water affinities came to dominate catches over time and demersal fisheries species also experienced a recent tropicalisation (Perez and Sant’Ana 2022). Effects of salinity were not assessed, and the roles of circulation changes including the role of the shifting Brazil Current were loosely considered, thus we have extremely low confidence about concluding whether future changes in S or in AMOC strength pose any risks to these species (mean risk scores of 0 and 2, respectively).

COMPARTMENTS	SOUTHEASTERN BRAZIL
	T assessed, S and AMOC not assessed but the role of southward expansion of the warmer Brazil Current and thus the location of the confluence with the Malvinas Current was considered.
	Mean temperature of the catch significantly increased by 0.41°C/year after 2013 until the dataset ended in 2019, in line with significantly increasing bottom seawater temperatures by 2013, and could represent a tipping point around 2012/2013. This tropicalisation of the fauna is in close agreement with INALT20 hindcasts in the Brazilian Meridional Margin, showing bottom temperature increases from 2013 to 2019 of 14.79–15.79°C. Early on (2000–2002), catches were dominated by many species with cooler water affinities like tope, Argentine conger, Argentine croaker, flounder, blackfin goosefish (monkfish), and white snake mackerel. Later on (by 2017–2019), catches were dominated more by species with warmer water affinities such as spotted pink shrimp, Atlantic bigeye, Florida pompano, whitemouth croaker, and grey triggerfish.
	Analysis at the South Atlantic Ocean basin-scale showed the temperature of the catch increased significantly and constantly since 1978. In the southwest Atlantic, sea surface temperature (SST) got warmer over time, with a 4 year time lag between SST increase and community changes and this effect was strong and significant. Catch biomass used to be characterised and dominated by cooler water species, mostly little tunny, Atlantic bonito, Atlantic bluefin tuna and albacore. But since 2004, catches are characterised by many more species and mostly those with warm water affinities.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	ICCAT species (T = 3, S = 0, AMOC = 1)
	demersal fisheries (T = 3, S = 0, AMOC = 1)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	ICCAT species (T = 2.5, S = 2.5, AMOC = 2)
	demersal fisheries (T = 2.5, S = 2.5, AMOC = 2)

	Score for T (Consequence x Likelihood)
	ICCAT species = 7.5
	demersal fisheries = 7.5
	Mean score for T overall = 7.5
	Score for S (Consequence x Likelihood)
	ICCAT species = 0
	demersal fisheries = 0
	Mean score for S overall = 0
	Score for AMOC (Consequence x Likelihood)
	ICCAT species = 2
	demersal fisheries = 2
	Mean score for AMOC overall = 2
	Combined mean score for T, S, AMOC changes
	ICCAT species = 3.17
	demersal fisheries = 3.17
	Total mean score for Study Region = 3.17


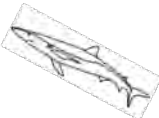
Summary Report – Study Region 11, Vitória-Trindade Seamount Chain

Overall, we have high confidence that **future changes in temperature will drive changes to oceanic fisheries species over the Vitória-Trindade Seamount Chain** (mean score of 7.5, out of a possible score of 9). Tuna, shark, and billfish with warmer water affinities came to dominate catches over time. Effects of salinity were not assessed, and the roles of circulation changes including the role of the shifting Brazil Current were loosely considered, thus we have extremely low confidence about concluding whether future changes in S or in AMOC strength will directly drive changes to these species (mean scores of 0 and 2, respectively).

COMPARTMENTS	VITÓRIA-TRINDADE SEAMOUNT CHAIN
	T assessed, S and AMOC were not assessed directly but the role of southward expansion of the warmer Brazil Current and thus the location of the confluence with the Malvinas Current was considered.
	Analysis at the South Atlantic Ocean basin-scale showed the temperature of the catch increased significantly and constantly since 1978. In the southwest Atlantic, sea surface temperature (SST) got warmer over time, with a 4-year time lag between SST increases and community changes and this effect was strong and significant. Catch biomass used to be characterised and dominated by cooler water species, mostly little tunny, Atlantic bonito, Atlantic bluefin tuna and albacore. But since 2004, catches are characterised by many more species and mostly those with warm water affinities.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	ICCAT species (T = 3, S = 0, AMOC = 1)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	ICCAT species (T = 2.5, S = 2.5, AMOC = 2)
	Score for T (Consequence x Likelihood)
	ICCAT species = 7.5
	Mean score for T overall = 7.5
	Score for S (Consequence x Likelihood)
	ICCAT species = 0
	Mean score for S overall = 0
	Score for AMOC (Consequence x Likelihood)
	ICCAT species = 2
	Mean score for AMOC overall = 2
	Combined mean score for T, S, AMOC changes
	ICCAT species = 3.17
	Total mean score for Study Region = 3.17

Summary Report – Study Region 12, Malvinas Current

Overall, we have extremely high confidence that **future changes in temperature will directly drive changes to both oceanic fisheries species and cold-water coral mounds located in around the Malvinas Current** (mean score of 9 out of a possible score of 9). Tuna, shark, and billfish with warmer water affinities came to dominate catches over time. Effects of T and S on cold-water coral mounds were assessed by $\delta^{18}O_{sw}$ proxies, showing coral proliferation when T and S were stable. Consequences of changes in S were not assessed for tuna, shark or billfish, so overall averaged over these species and coral mounds, we end up with low confidence in concluding about the ecosystem consequences of future changes in S (mean score of 3.75). The same is true for AMOC changes: these are expected to have strong and significant consequences for coral mounds but not for oceanic species (mean score of 4).

COMPARTMENTS	MALVINAS CURRENT
	T assessed, S and AMOC assessed for coral mounds but not for ICCAT species, though role of upwelling cells was considered.
	The most prolific coral growth phase during HS-1 coincided with periods of stable T and S (proxied by $\delta^{18}O_{sw}$) and other factors including oxygen (proxied by benthic foraminiferal- Mn/Ca ratio), high total organic carbon concentrations, and hydrodynamic factors including a breakdown in AMOC that likely reduced North Atlantic Deep Water (NADW) flow to the site causing a downward shift of Antarctic Intermediate Water (AAIW) and the Circumpolar Deep Water (CDW) interface, which would have increased hydrodynamic energy triggering internal waves that help deliver food particles and thereby to fuel cold-water coral ecosystems. Possible tipping points marked by increased environmental variability and slower coral and mound growth rates occurred 14–12 kyr BP and from 11–8 kyr BP, the latter phase finally terminating when hydrodynamic energy and food supply decreased.
	Analysis at the South Atlantic Ocean basin-scale showed the temperature of the catch increased significantly and constantly since 1978. In the southwest Atlantic, sea surface temperature (SST) got warmer over time, with a 4-year time lag between SST increases and community changes and this effect was strong and significant. Catch biomass used to be characterised and dominated by cooler water species, mostly little tunny, Atlantic bonito, Atlantic bluefin tuna and albacore. But since 2004, catches are characterised by many more species and mostly those with warm water affinities.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	ICCAT species (T = 3, S = 0, AMOC = 1)
	coral mounds (T = 3, S = 3, AMOC = 3)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)

	ICCAT species (T = 3, S = 2.5, AMOC = 2)
	coral mounds (T = 3, S = 2.5, AMOC = 2)
	Score for T (Consequence x Likelihood)
	ICCAT species = 9
	coral mounds = 9
	Mean score for T overall = 9
	Score for S (Consequence x Likelihood)
	ICCAT species = 0
	coral mounds = 7.5
	Mean score for S overall = 3.75
	Score for AMOC (Consequence x Likelihood)
	ICCAT species = 2
	coral mounds = 6
	Mean score for AMOC overall = 4
	Combined score for T, S, AMOC changes
	ICCAT species = 3.67
	coral mounds = 7.5
	Total mean score for Study Region = 5.59

Summary and Recommendations

The assessments conducted in this study can support iAtlantic in highlighting which Study Regions could benefit from ramping up investments and allocating resources for ocean observations and ecosystem monitoring. It also supports the project in identifying which oceanographic parameters and ecosystem compartments to monitor over the next few decades, and identify critical knowledge gaps, which helps to prioritise future research but also which supports adaptive management.

These recommendations should never supersede the extraordinary long-term time series monitoring and surveys taking place in iAtlantic's 12 Study Regions, including the many long-standing and highly regarded government and industry surveys, and those coming from ocean observatories. These surveys and programmes have regional, national, and international value to scientists and policy-makers alike. These are often used to assess ecosystem health, effectiveness of management measures, status of fish stocks, and contribute to global ocean observation systems. With a lack of time series in the deep and open ocean generally, the sustained surveys already taking place were crucial in enabling iAtlantic to improve our understanding of drivers of change and identify possible tipping points. Thus, the recommendations below suggest a series of enhancements and possible focal areas where ecosystem changes are most likely and thus where monitoring could be ramped up to detect and therefore adapt and mitigate as quickly as possible. In this way, we can recommend sentinel regions.

The following summary (also see [Table 2](#) and [Figure 3](#)) provides a high-level overview of which Study Regions we are most confident will experiencing strong and significant alterations to the ecosystem components directly due to changes in the strength of AMOC, temperature and salinity. It also provides an overview of which oceanographic trends we are most confident are related to these trends going forward in which case we need to ensure these EOVs are being measured in consistent and harmonised ways across the Atlantic.

Table 2: Confidence assessment of forecasted sea temperatures, salinities, and AMOC strength by Study Region. Scores highlighted in red indicate a high level of confidence in our assessments, and yellow highlight indicates less confidence, with no colour indicating very low to no confidence that changes in AMOC, S, or T will directly impact the ecosystems we studied.

	Mean score for T	Mean score for S	Mean score for AMOC	Combined score
ICELAND	8.7	6	2	5.57
PORCUPINE ABYSSAL PLAIN	3	0	0	1.00
LUCKY STRIKE	4.5	3	2	3.17
SCOTIAN SLOPE	4.5	3	0	2.50
SARGASSO SEA	4.46	2.23	1.2	2.63
CAPE VERDE	1.07	0	1	0.69
ROMANCHE FRACTURE ZONE	4.5	0	2	2.17
ANGOLA TO CONGO LOBE	6.75	3.75	2	4.17
WALVIS RIDGE TO SOUTH AFRICA	3	0	2	1.67
SOUTHEASTERN BRAZIL	7.5	0	2	3.17
VITÓRIA-TRINDADE SEAMOUNT CHAIN	7.5	0	2	3.17
MALVINAS CURRENT	9	3.75	4	5.58

Sentinel regions to monitor and ecosystem time series to sustain

Table 2 illustrates an interesting finding: we have the greatest confidence that assessments in our Arctic-Atlantic and Atlantic-Antarctic frontier Study Regions in Iceland and the Malvinas Current, respectively. This means we are most confident that the ecosystem compartments we studied around Iceland and in the Malvinas Current are likely to experience direct consequences from the changes in AMOC strength, T, and S forecasted under the high emission future scenario (**Table 2**). Recall these were also the two Study Regions with the highest likelihood of oceanic changes in the future (**Figure 2**) and thus had high combined scores (**Figure 3**).

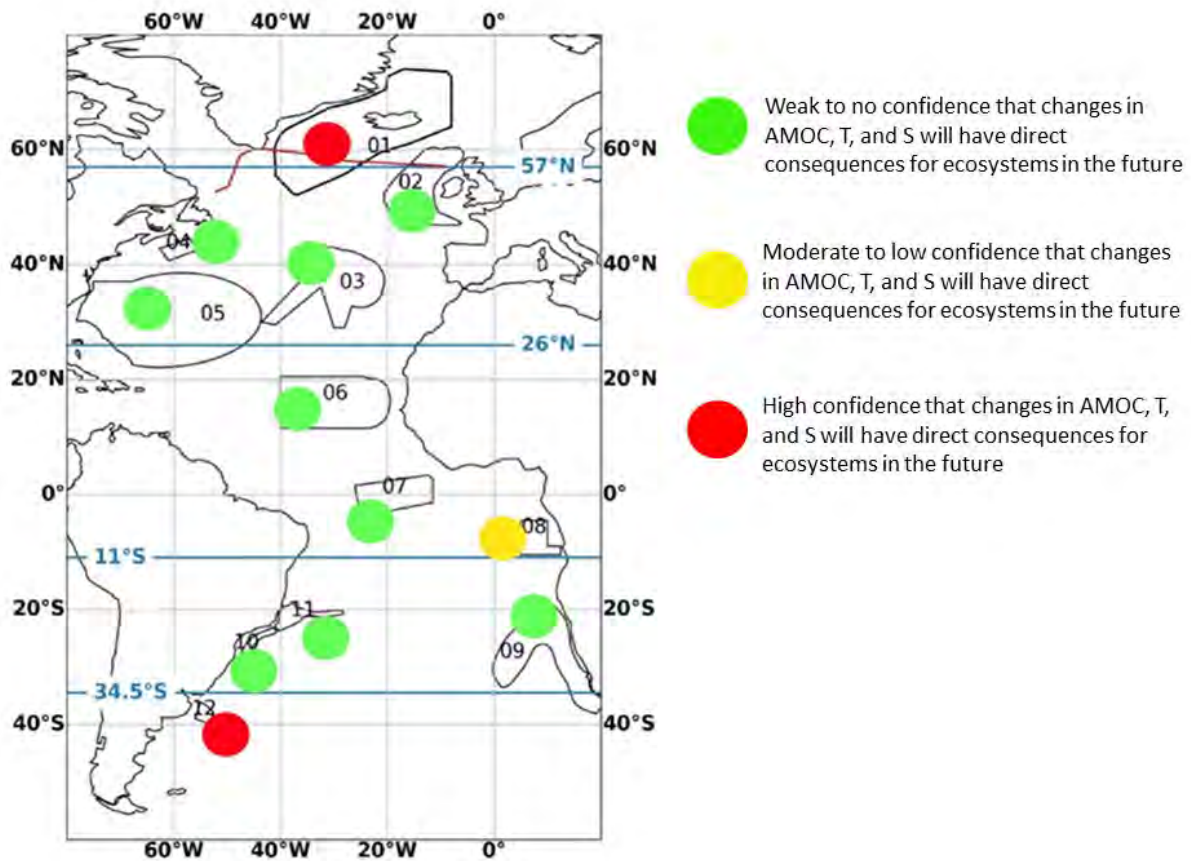


Figure 3: Combined scores (Likelihood of AMOC, T, and S changes averaged across water masses X Consequences to ecosystems relating directly to these changes, averaged across components for iAtlantic’s 12 Study Regions). Note there is high confidence that future changes to AMOC, T, and S at high latitudes will directly impact and lead to ecosystem changes in those Study Regions.

Both the Iceland and the Malvinas Current included time series over geological and ecological time scales, but the ecosystem compartments studied were very different. In Iceland, changes in foraminiferans, groundfish, capelin, and humpback whales were all observed, with important roles for AMOC, T, and S identified though it was challenging to pinpoint particular drivers for, e.g., relationships between humpback whale numbers and T or S. Around the Malvinas current, changes in cold-water coral ecosystems and highly migratory fish stocks were observed and closely linked to T but also S, and the AMOC especially for coral mounds. Unmitigated human activities and future blue growth strategies must account for these risks so as to avoid tipping these ecosystems into new ecosystem states or regimes.

There could be many explanations for why we observed the highest scores in our high latitude Study Regions, and these are probably not mutually exclusive. One explanation is the mis-match in spatial and temporal scales considered in these two Study Regions resulted in a spuriously high combined score. For example, there was a mis-match about how quickly changes in T could impact coral mounds versus tuna, billfish, and migratory sharks with the former studied over centennial to millennial timescales and the latter time series constructed over about 30 years. Furthermore, impacts of T on highly migratory fish stocks were widespread in the South Atlantic and not just constrained to those in the Malvinas Current as the dataset was analysed at the larger spatial scale of the southwestern Atlantic. While a widespread 'marine tropicalisation' in thermal niches for these animals seems to have occurred across the South Atlantic (Perez and Sant'Ana 2022 and see *Deliverable 3.2*), it's also important to remember that while 'Consequences' of T change was always high for this ecosystem component, the 'Likelihood' of these changes in T taking place in the future differed across Study Regions. Thus, while effects of future changes in T on these animals will not be constrained to just the Malvinas Current, the higher 'Likelihood' of this change may have artificially inflated the scores here especially with the already high scores for the effects these can have on cold-water coral mounds.

Another explanation could be that the high combined scores for these two Study Regions are artefacts of AMOC and salinity both considered as potential drivers of ecosystem change in these regions. Integrating (averaging) scores over water masses, followed by averaging across scores to derive the combined scores, may erase the subtle nuances of ecosystem impacts driven by a single factor. Thus, if an ecosystem time series analysis from *Deliverable 3.2* did not include, or confidently conclude, any relationship to T, S, or AMOC, then its combined score would necessarily be lower. For example, the study on the growth history of cold-water coral mounds in the Malvinas Current explicitly accounted for changes in circulation strength and salinity on these ecosystems, whereas other Study Regions did not examine the influence of these variables, or did so but indirectly.

An alternative but not mutually exclusive explanation is that strong and significant ecosystem change in deep and open ocean ecosystems could be more likely to occur at the frontiers between boreal and polar regions. *Deliverable 3.2* reported loss of species with cooler water affinities over time in many Study Regions coincident with large scale rising sea temperatures or background cycles of warming and cooling over the past few decades. In general, recent marine species extirpations attributable to ocean warming have occurred where species are living nearest to their upper thermal tolerance limits (Pinsky et al. 2019). Many marine species exhibit behavioural thermoregulation from zooplankton to crustaceans, to tuna, pelagic sharks and cetaceans, moving deeper or over larger areas to find more suitable niches and some have great adaptive potential.

However, there is evidence that at least some marine species at higher latitudes exhibit far less tolerance to thermal changes than those at lower latitudes and may be more severely impacted (Sunday et al. 2011). Thus, our first recommendation is that **ramping up investments in monitoring and mitigating ecosystem changes in these 'sentinel' regions and using 'sentinel' species or ecosystems** is going to be particularly important in any management or decision-making regime. While it is advised to continue the collection of all time series used in WP 3 to create and maintain long term sustained observations at the Atlantic Ocean scale, *Deliverable 3.3* highlights the value in ensuring Iceland's time series are maintained in particular. Capelin showed clear direct effects of T, S, and AMOC, and with a strong dependence of the blue economy on this transboundary resource, it's critical we improve our understanding of how climate change may impact these shared stocks and adapt management in order to mitigate any risks of climate change. Iceland's demersal fish including monkfish datasets also proved extremely valuable in demonstrating clear direct effects from T and S changes, so it's advised to also

maintain these to continue tracking such strong and significant shifts in these commercially important stocks. Palaeoceanographic data are critical in understanding the very long-term role that AMOC, T, and S changes can bring to our high latitude Study Regions around Iceland and in the Malvinas Current, so it's advised to maintain these as well and expand sampling in these regions to continue building up that picture. For example, iAtlantic WP 3 research demonstrated the promising use of marine sedimentary ancient DNA (*sedaDNA*) (Selway et al. 2022), which could help unlock new time series from sediment cores in these regions.

What kinds of investments and resourcing are needed to monitor and co-operate?

In terms of which oceanographic parameters and ecosystems to monitor, [Table 2](#) also illustrates that we have high levels of confidence that changes in water temperature are likely to continue to be strong, and significant drivers of ecosystem change in our Study Regions. This evidence underpins our second recommendation to **ensure adequate investment and resourcing** in collecting and sharing sustained *in situ* and full depth temperature measurements across the Atlantic. *In situ* measurements are critical for monitoring ocean health and can serve as ecosystem health 'thermometer' (O'Brien et al. 2017) with the standard variables considered here in *Deliverable 3.3* (AMOC, T, and S) also being EOVs. *In situ* observations are also critical to develop and validate both ocean and climate models (O'Brien et al. 2017), and it's important we invest appropriately at the local and regional levels but also in ways that facilitate co-operation and data sharing across regions. Standardisation of measurements obtained by the OSNAP (57°N), RAPID (26°N), TRACOS (11°S), and SAMOC (34.5°S) arrays are now well underway in part fuelled by calls to collaborate under the Galway and Belém Statements and South-South co-operation agreements.

However, similar long-term time series of the ecological side of ecosystems in these 12 Study Regions are still lacking across a fuller range of components from the marine food webs of each region. Therefore, it has been difficult to join these kinds of time series up at the basin-scale, because each region has its own priorities and capacities, and methods to collect the data in the first place. Thus, the time series analysed in *Deliverable 3.2* (and described in *Deliverable 3.1*) still remain the key ecosystems we should continue to study in these 12 regions if we are to keep improving the understanding of temporal change in deep-sea and open ocean ecosystems here and the impacts of any management measures put in place. Wherever possible, time series in these regions should ensure they are capturing temporal changes at the surface, through the water column, and at the seafloor, and the combined risk scores ([Table 2](#)) can be easily updated as new ecosystem components are added. For example, with extra human capacity, one could analyse the tuna, billfish and sharks monitored by the International Commission for the Conservation of Atlantic Tunas (ICCAT) in the North Atlantic, to see if a climate signal (a marine 'tropicalisation') has also occurred in the northern hemisphere as it has for the South Atlantic, or whether one basin is more at risk than another. With new infrastructure and vessel capacity to sample zooplankton and mesopelagic fish in the deep and open ocean areas of the South Atlantic, we could align those observations with those in the north. Another example for investment would be establishing sustained open ocean and deep-sea observation platforms in the South Atlantic, e.g., the industry-led DELOS ('Deep-ocean Environmental Long-term Observatory System') project created a research programme that was used to monitor the ecosystems at two seafloor observatories since 2013 (Vardaro et al. 2013). Alongside that are needs to ramp up investments in deep-sea research in Study Regions like off South Africa to include access to vessels and personnel training (Sink et al. 2021).

Going forward, harmonising data collection and datasets are critical steps so we can scale up the understanding. However, the iAtlantic place-based approach gave us the flexibility (and resilience

to the covid-19 pandemic) to work with pre-existing data that were collected often for other purposes in each region using equipment and methods relevant to that region, with whatever human capacity existed at that time, without needing upfront investments to re-invent the wheel.

How can we grow our capacity to obtain and co-operate on ecosystem time series?

We are most confident temperature changes throughout the water column are going to have the greatest consequences for ecosystems around Iceland, Angola to Congo Lobe, and from the Vitória-Trindade Seamounts to southeastern Brazil and the Malvinas Current. Most of the ecosystem compartments analysed in these regions are closely tied to the Atlantic blue economy including marine wildlife watching (humpbacks), commercial fisheries (groundfish and pelagic stocks), and sport fishing (tuna, shark and billfish). Many of these species (but not all) are also marine top predators, changes in which can indicate wider ecosystem changes that haven't been monitored or observed by humans (Hazen et al. 2019). The DELOS project off Angola was mentioned earlier too, as an example of a way to create opportunities to make sustained deep ocean observations and was funded by the offshore energy industry (Vardaro et al. 2013). The findings and recommendations in this Deliverable show how we can better prioritise not only which ecosystem compartments to keep monitoring through existing time series, but also how to sustain this monitoring. Thus, our third recommendation is that **building and maintaining public-private partnerships, industry collaborations, and data-sharing mechanisms across diverse knowledge systems** can greatly enable such assessments and help authorities, planners and other actors take effective action where and when needed. These partnerships have been at the heart of the iAtlantic approach to its work (Roberts et al. 2023). Beyond long-term users of the ocean such as commercial fisheries, oil and gas, telecommunications, and shipping, and due to the migratory and/or charismatic nature of many of these animals from coast to the open ocean, we could actively engage a wider range of knowledge holders to help create new time series. Future initiatives should actively reach out to marine wildlife tourism operators, bodies that represent small-scale fishers like the International Pole and Line Foundation (IPLF), sea anglers including their representative bodies like the International Game Fish Association (IGFA), and the emerging deep-sea tourism, which can also help reveal the links and feedbacks between socioeconomies, impacts of climate change, and the environment in a fully coupled socio-ecological system.

Political will and the broader use of Area-Based Management Tools (ABMTs) for mitigation

Measures to mitigate climate change could substantially slow its pace and avoid, or at least reduce, the impacts of the associated stressors on marine species and ecosystems (Henson et al. 2017). The assessments presented in this Deliverable illustrate high confidence that changes in ocean temperature will continue to drive strong and significant changes in deep and open ocean Atlantic ecosystems (Table 2). Thus, our fourth and final recommendation is that **mitigating risks from temperature change will require very strong political commitment** to reducing greenhouse gas emissions. This is so we don't reach the worst-case scenario and we can avoid those consequences in the first place, or at least reduce and ameliorate the impacts. A less severe emission scenario will likely mean that marine ecosystems experience far fewer abrupt shifts or cross tipping points (Cael et al. 2021). But this will require re-examining our marine governance systems to ensure seamless and timely inter-agency co-operation from the global to local scale (Heinze et al. 2021) and ensuring authorities take substantive actions (Sunby et al. 2021).

Besides avoiding or reducing the risk of reaching the worst-case emission scenario, mitigation can also include measures to restore ecosystems and increase their resilience through the effective use

of area-based management tools (ABMTs). Restoring and rebuilding fish stocks is multifaceted and for species that in particular exhibited strong and significant relationships with temperature, the use of total allowable catch (TACs) is critical, but the toolbox open to authorities is much more varied (see Hilborn et al. (2022)). It is not immediately clear how ABMTs could contribute to increase resilience in pelagic habitats (e.g., feeding and spawning areas) as these are dynamic shifting in space due to climate change but ABMTs could be appropriate to these habitats if these managed areas can be changed adaptively (Hilborn et al. 2022). Such adaptive tools could then protect dynamic features such as core species' ranges, larval and early life stage source areas, and 'blue corridors' (sensu Johnson et al. (2022)) but also more static features such as stepping stones that maintain ecological connectivity and climate refugia.

To make this a reality, an ABMT portfolio should not only include marine protected areas (MPAs) but also other types of area-based measures. For example, since 2003, various landmark UN General Assembly Sustainable Fisheries resolutions have called for urgent action to protect vulnerable marine ecosystems (VMEs) including 58/14 (2003), 59/25 (2004) and 61/105 (2006). These resolutions legally bind States and Regional Fisheries Management Organisations to various types of ABMT and measures that protect VMEs including having to undertake impact assessments, enacting fisheries closures, and ensuring sustainable levels of catch and bycatch. The effective use of marine spatial planning (MSP), strategic environmental assessment (SEA), and environmental impact assessment (EIA) are also forms of ABMTs, all of which have technical guidance on how to integrate climate change into such ocean planning instruments. The use of other effective area-based conservation measures (OECMs) has not been exploited in the deep and open Atlantic Ocean. Some of these may provide stronghold habitats and even climate refugia for deep and open ocean species, e.g., the occurrence of listed species of cold-water coral on oil and gas platforms could make the meta-population more resilient as these structures are predicted to remain suitable habitat even under ocean warming and acidification conditions (Henry et al. 2018). It is feasible to think these could include, for example, designation of shipwrecks and decommissioned offshore infrastructure as OECMs if the management measures around these have objectives that indirectly end up protecting species and ecosystems. A full suite of ABMTs helps keep marine species and ecosystems connected, healthy, and thus more resilient to perturbations from human activities and climate change.

To conclude, we re-state our four key recommendations arising from our confidence assessments:

- ✓ ramp up investments in monitoring and mitigating ecosystem changes especially at high latitudes where we are confident that changes in AMOC, T, and S are going to drive further changes in deep and open ocean ecosystems;
- ✓ ensure adequate investment and resourcing to collect and share sustained full depth temperature observations across the Atlantic, particularly in sentinel regions and the South Atlantic;
- ✓ build and maintain public-private partnerships, industry collaborations, and data-sharing mechanisms across diverse knowledge systems to enable similar or repeat assessments;
- ✓ deliver on commitments to slow the pace of global climate change, and use a portfolio of ABMTs to increase resilience.

References

- Brito-Morales, I., Schoeman, D. S., Molinos, J. G., Burrows, M. T., Klein, C. J., Arafeh-Dalmau, N., ... & Richardson, A. J. (2020). Climate velocity reveals increasing exposure of deep-ocean biodiversity to future warming. *Nature Climate Change*, 10(6), 576–581. <https://doi.org/10.1038/s41558-020-0773-5>
- Cael, B. B., Dutkiewicz, S., & Henson, S. (2021). Abrupt shifts in 21st-century plankton communities. *Science advances*, 7(44), eabf8593. <https://doi.org/10.1126/sciadv.abf8593>
- Hall, G., Webber, M. (2022). Chapter 26: Maritime security in the North Atlantic. In Boşilcă, R.L., Ferreira, S., Ryan, B.J. (Eds.), *Routledge Handbook of Maritime Security*.
- Hazen, E. L., Abrahms, B., Brodie, S., Carroll, G., Jacox, M. G., Savoca, M. S., ... & Bograd, S. J. (2019). Marine top predators as climate and ecosystem sentinels. *Frontiers in Ecology and the Environment*, 17(10), 565–574. <https://doi.org/10.1002/fee.2125>
- Heinze, C., Blenckner, T., Martins, H., Rusiecka, D., Döscher, R., Gehlen, M., ... & Wilson, S. (2021). The quiet crossing of ocean tipping points. *Proceedings of the National Academy of Sciences*, 118(9), e2008478118. <https://doi.org/10.1073/pnas.2008478118>
- Henry, L. A., Mayorga-Adame, C. G., Fox, A. D., Polton, J. A., Ferris, J. S., McLellan, F., ... & Roberts, J. M. (2018). Ocean sprawl facilitates dispersal and connectivity of protected species. *Scientific reports*, 8(1), 11346. <https://doi.org/10.1038/s41598-018-29575-4>
- Henson, S. A., Beaulieu, C., Ilyina, T., John, J. G., Long, M., Séférian, R., ... & Sarmiento, J. L. (2017). Rapid emergence of climate change in environmental drivers of marine ecosystems. *Nature Communications*, 8(1), 14682. <https://doi.org/10.1038/ncomms14682>
- Hilborn, R., Agostini, V. N., Chaloupka, M., Garcia, S. M., Gerber, L. R., Gilman, E., ... & Fitchett, M. (2022). Area-based management of blue water fisheries: Current knowledge and research needs. *Fish and Fisheries*, 23(2), 492-518. <https://doi.org/10.1111/faf.12629>
- Johnson, C., Reisinger, R., Palacios, D., Friedlaender, A., Zerbini, A., Willson, ... & Kelez, S. (2022). *Protecting Blue Corridors, Challenges and Solutions for Migratory Whales Navigating International and National Seas*. WWF, Oregon State University, University of California, Santa Cruz, Publisher: WWF International, Switzerland, 136pp
- Liu, M., & Tanhua, T. (2021). Water masses in the Atlantic Ocean: characteristics and distributions. *Ocean Science*, 17(2), 463–486. <https://doi.org/10.5194/os-17-463-2021>
- Matthes, K., Biastoch, A., Wahl, S., Harlaß, J., Martin, T., Brücher, T., ... & Park, W. (2020). The flexible ocean and climate infrastructure version 1 (FOCI1): Mean state and variability. *Geoscientific Model Development*, 13(6), 2533–2568. <https://doi.org/10.5194/gmd-13-2533-2020>
- Miloslavich, P., Bax, N. J., Simmons, S. E., Klein, E., Appeltans, W., Aburto-Oropeza, O., ... & Shin, Y. J. (2018). Essential ocean variables for global sustained observations of biodiversity and ecosystem changes. *Global Change Biology*, 24(6), 2416–2433. <https://doi.org/10.1111/gcb.14108>
- Meinshausen, M., Vogel, E., Nauels, A., Lorbacher, K., Meinshausen, N., Etheridge, D. M., ... & Weiss, R. (2017). Historical greenhouse gas concentrations for climate modelling (CMIP6). *Geoscientific Model Development*, 10(5), 2057–2116. <https://doi.org/10.5194/gmd-10-2057-2017>
- O'Brien, T. D., Lorenzoni, L., Isensee, K., & Valdés, L. (2017). What are Marine Ecological Time Series telling us about the ocean. *A status report. IOC Tech. Ser.*, 129, 1–297.
- Perez, J. A. A., & Sant'Ana, R. (2022). Tropicalization of demersal megafauna in the western South Atlantic since 2013. *Communications Earth & Environment*, 3(1), 227. <https://doi.org/10.1038/s43247-022-00553-z>
- Pinsky, M. L., Reygondeau, G., Caddell, R., Palacios-Abrantes, J., Spijkers, J., & Cheung, W. W. (2018). Preparing ocean governance for species on the move. *Science*, 360(6394), 1189–1191. <https://doi.org/10.1126/science.aat2360>
- Pinsky, M. L., Eikeset, A. M., McCauley, D. J., Payne, J. L., & Sunday, J. M. (2019). Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature*, 569(7754), 108-111.

- <https://doi.org/10.1038/s41586-019-1132-4>
- Roberts, J. M., Devey, C. W., Biastoch, A., Carreiro-Silva, M., Dohna, T., Dorschel, B., ... & Henry, L. A. (2023). A blueprint for integrating scientific approaches and international communities to assess basin-wide ocean ecosystem status. *Communications earth & environment*, 4(1), 12. <https://doi.org/10.1038/s43247-022-00645-w>
- Selway, C. A., Armbrrecht, L., & Thornalley, D. (2022). An outlook for the acquisition of marine sedimentary ancient DNA (sedaDNA) from North Atlantic Ocean Archive Material. *Paleoceanography and Paleoclimatology*, 37(5), e2021PA004372. <https://doi.org/10.1029/2021PA004372>
- Sink, K.J., McQuaid, K., Atkinson, L.J., Palmer, R.M., Van der Heever, G., Majiedt, P.A., ... & Patterson, A.W. (2021). Challenges and Solutions to develop capacity for deep-sea research and management in South Africa. *South African National Biodiversity Institute*, 35pp
- Sumby, J., Haward, M., Fulton, E. A., & Pecl, G. T. (2021). Hot fish: The response to climate change by regional fisheries bodies. *Marine Policy*, 123, 104284. <https://doi.org/10.1016/j.marpol.2020.104284>
- Sunday, J. M., Bates, A. E., & Dulvy, N. K. (2011). Global analysis of thermal tolerance and latitude in ectotherms. *Proceedings of the Royal Society B: Biological Sciences*, 278(1713), 1823–1830. <https://doi.org/10.1098/rspb.2010.1295>
- Vardaro, M. F., Bagley, P. M., Bailey, D. M., Bett, B. J., Jones, D. O., Milligan, R. J., ... & Clarke, J. (2013). A Southeast Atlantic deep-ocean observatory: first experiences and results. *Limnology and Oceanography: Methods*, 11(6), 304–315. <https://doi.org/10.4319/lom.2013.11.304>

Supplementary Information

Appendix I – Ocean forecasts for North Atlantic Study Regions

Integration of ecosystem time series across their respective water masses and the derivation of mean Likelihood scores for temperature (T) and salinity (S) according to Appendix F in *Deliverable 1.2*. Values in bold type were significant at 95% confidence intervals. Values in rows in highlighted by grey are those brought forward to derive scores for each ecosystem compartment. ISOW = Iceland Scotland Overflow Water; ENACW = Eastern North Atlantic Central Water; LSW = Labrador Sea Water; NEABW = Northeast Atlantic Bottom Water; NADW = North Atlantic Deep Water; SBJW = Shelf Break Jet Water; STUW = Sub Tropical Under Water; TSW = Tropical Surface Water; AAIW = Antarctic Intermediate Water.

Study Region	Water depths of observations (m)	Water mass (Appendix F in Deliverable 1.2)	(Mean) Likelihood for T	(Mean) Likelihood for S	AMOC	T ₁	S ₁	T ₂	S ₂	T ₃	S ₃	T ₄	S ₄	T ₅	S ₅	T ₆	S ₆	T ₇	S ₇
Iceland																			
forams	2303, 2311 and 2630	ISOW	(2+3)/2=2.5	(3+3)/2=3	2	-0.01	-0.005												
forams	1299 and 1310	ENACW			2	-0.05	-0.01												
demersal fisheries	20 - 500 (mean about 190)	ENACW	(3+3)/2=3	(3+3)/2=3	2	-0.05	-0.01	0.07	0.007										
demersal fisheries	25 - 1420 (mean about 400)	ENACW and LSW			2	-0.05	-0.01	0.07	0.007										
monkfish	20 - 500 (mean about 190)	ENACW and LSW	(3+3)/2=3	(3+3)/2=3	2	-0.05	-0.01	0.07	0.007										
monkfish	25 - 1420 (mean about 400)	ENACW and LSW			2	-0.05	-0.01	0.07	0.007										
capelin		ENACW	3	3	2	-0.05	-0.01												
humpbacks	0 but move vertically	ENACW	3	3	2	-0.05	-0.01												
Porcupine Abyssal Plain																			
PAP data		NEABW	3	3	2	-0.06	-0.007												
Lucky Strike																			
vent fauna		upper NADW	3	3	2	-0.11	-0.023												
Scotian Slope																			
NS demersals	100-730	SBJW and ENACW	(3+3)/2=3	(3+3)/2=3	2	0.42	0.123	0.06	0.023										
NS cetaceans	0 but move vertically	SBJW	3	3	2	0.42	0.123												
NS zooplankton	0-1000	SBJW, ENACW	(3+3)/2=3	(3+3)/2=3	2	0.42	0.123	0.06	0.023										
cetaceans	0 but move vertically	SBJW	3	3	2	0.42	0.123												
Sargasso Sea																			
BATS data	full depth	STUW to NEABW	(3+3+2+3+0+3+3)/7=2.43	(3+3+2+3+0+2+3)/7=2.14	2	0.21	0.076	0.1	0.035	0.01	0.002	na	na	-0.06	-0.015	0.02	0.002	-0.03	-0.004
BATS zooplankton	150-200	STUW	3	3	2	0.21	0.076												
humpback data	0 but move vertically	STUW	3	3	2	0.21	0.076												
forams & diatoms	full depth	STUW and NEABW	(3+3+2+3+0+3+3)/7=2.43	(3+3+2+3+0+2+3)/7=2.14	2	0.21	0.076	0.1	0.035	0.01	0.002	na	na	-0.06	-0.015	0.02	0.002	-0.03	-0.004
Cape Verde																			
iMirabilis forams		TSW	0	0	2	na	na												
CVOO zooplankton		TSW to AAIW	(0+3+3+3+3)/5=2.4	(0+3+3+3+3)/5=2.4	2	na	na	0.11	0.048	-0.1	-0.033	-0.07	-0.02	0.07	0.014				

Appendix II – Ocean forecasts for South Atlantic Study Regions

Integration of ecosystem time series across their respective water masses and the derivation of mean Likelihood scores for temperature (T) and salinity (S) according to Appendix F in *Deliverable 1.2*. Values in bold type were significant at 95% confidence intervals. Values in rows in highlighted by grey are those brought forward to derive scores for each ecosystem compartment. TSW = Tropical Surface Water; STUW = Sub Tropical Under Water; ESACW = Eastern South Atlantic Central Water; AAIW = Antarctic Intermediate Water; WSACW = Western South Atlantic Central Water; SASW = SubAntarctic Shelf Water.

Study Region	Water depths of observations (m)	Water mass (Appendix F in Deliverable 1.2)	(Mean) Likelihood for T	(Mean) Likelihood for S	AMOC	T ₁	S ₁	T ₂	S ₂
Romanche Fracture Zone									
RFZ ICCAT	0 but move vertically	TSW and STUW	(0+3)/2=1.5	(0+3)/2=1.5	2	na	na	0.11	0.048
Angola to Congo Lobe									
Angola corals	247 to 457	ESACW and AAIW	(3+2)/2=2.5	(3+2)/2=2.5	2	-0.13	-0.026	-0.04	-0.002
Angola ICCAT	0 but move vertically	STUW and WSACW	(2+2)/2=2	(3+2)/2=2.5	2	0.05	0.007	-0.01	-0.005
Walvis Ridge to South Africa									
Walvis ICCAT	0 but move vertically	WSACW and ESACW	(0+3)/2=1.5	(0+3)/2=1.5	2	0	0	-0.06	-0.015
Vitória-Trindade Seamounts									
V-T ICCAT	0 but move vertically	STUW and WSACW	(3+2)/2=2.5	(3+2)/2=2.5	2	0.12	0.042	0.01	0.004
Southeast Brazil									
SE Brazil ICCAT demersal fisheries	0 but move vertically down to 500m	STUW and WSACW	(2+3)/2=2.5	(2+3)/2=2.5	2	0.07	0.018	-0.03	-0.01
Malvinas Current									
Malvinas ICCAT	0 but move vertically	SASW and ESACW	(3+3)/2=3	(3+2)/2=2.5	2	0.04	0.011	0.04	0.002
Malvinas corals	992 to 1202	ESACW and AAIW	(3+3)/2=3	(2+3)/2=2.5	2	0.04	0.002	0.05	0.011

Supplementary Material 1: Worked example of scoring Consequences using a zooplankton case study from Study Region 4: the Scotian Slope, Northwest Atlantic




To help illustrate the scoring used to implement *Deliverable 3.3*, a worked example is provided below. Scores are assigned based on the Methods described earlier, and based on what was reported by analysts in *Deliverable 1.2* and *Deliverable 3.2* and based on depth-dependent and then averaged scores of Likelihood assigned in Appendices I and II.

The worked example below is from Study Region 4, off Nova Scotia, in the Northwest Atlantic. Several time series were compiled and analysed using a standardised workflow (described in *Deliverable 3.1*) to generate results on how strong and statistically significant effects of T, S, and AMOC were on these time series. Expert judgement was used in this case study, with experts from the Canadian Department of Fisheries and Oceans and the University of Edinburgh agreeing that effects of AMOC would not be assessed for this Study Region because any possible relationships between AMOC and these ecosystem compartments would be spurious at best, and not truly indicate a clear and direct relationship. This was thought to be because time series were not considered long enough to capture strong shifts in AMOC strength (e.g., demersal fish) or because drawing a clear interpretation would simply be just by chance as compartments respond to multiple environmental drivers and maybe more local ones, e.g., cetaceans.

To calculate 'Consequence', in *Deliverable 3.2*, experts analysed time series for zooplankton communities sampled at different seasons, stratified across depths, from 1999-2019 on the Scotian Slope.

- Effects of T on zooplankton were found to be strong and statistically significant in *Deliverable 3.2*, so this is scored as a 3 (Major Change).
- Effects of S on zooplankton did not exert strong or significant effects on zooplankton, but community trajectories were changing alongside increases in salinity, so this is scored as a 2 (Minor Change), it was just that T showed far more direct and strong links, especially as the zooplankton did take on more of a warm water character over time.
- Effects of AMOC on zooplankton were not assessed in this Study Region as experts deemed zooplankton dynamics to be forced more by regional scale dynamics in the region that were best captured by other variables for which the analysts had environmental data, e.g., T, S, but also chlorophyll a measurements. Thus, effects of AMOC were not assessed in order to avoid finding any misleading and spurious relationships, and so given a score of 0 (Not Assessed); note however, a post hoc analysis of these data (see Supplementary Material 1) indeed illustrated that despite a change in AMOC strength in the late 1990s, this did not coincide breakpoints detected by statistical analyses reported in *Deliverable 3.2* for either zooplankton or demersal fish data in Study Region 4 (zooplankton data: 2008 and 2014; demersal fish data: 1996 and 2012).

Below is the overall score calculations for all the compartments, which can be tracked back to results in *Deliverables 1.2* and *3.2*, and the depth-averaged Likelihood scores in Appendices I and II.

COMPARTMENTS	SCOTIAN SLOPE
	T directly assessed, S not directly assessed, circulation not assessed
	Warmer water zooplankton species are becoming more characteristic, which is strongly and significantly related to T. Breakpoints occurred in 2008 (for autumn datasets) and 2014 (for spring datasets). All <i>Calanus hyperboreus</i> life stages are declining in abundance, with breakpoints in 2006 and 2014 (in spring datasets) and in 2010 (in autumn datasets), with significant effects of T but this could relate to timings of spring blooms too. Spring declines are strongly and significantly related to T and chlorophyll a concentration, but autumn declines are inconclusive. T and S have increased between the mixed layer depth and 200 m since 2010.
	Species abundance has decreased over time in shallow strata, e.g., monkfish, witch flounder, and Atlantic halibut. Blackbelly rosefish, sand lance and shortfin squid have become more abundant. Breakpoints occurred at different times across the region: in 1996 and 2012 in shallow strata, and 2004 in the deep strata. The 1995/1996 breakpoint corresponded with a shift from a negative to a positive Atlantic Multi-decadal Oscillation.
	Sightings of long-finned pilot whales and beaked whales in the Gully Marine Protected Area have generally increased over time since 1988, while Atlantic white-sided dolphins and short-beaked common dolphin have decreased. Drivers are likely species-specific and involve multiple biophysical interactions as well as possible effects of underwater noise mitigation measures in the area as opposed to effects of AMOC, T, or S.
	Consequence (Major changes = 3, Minor Changes = 2, Inconclusive = 1, Not Assessed = 0)
	zooplankton (T = 3, S = 2, AMOC = 0)
	<i>Calanus</i> life stages (T = 2, S = 1, AMOC = 0)
	demersal fisheries (T = 1, S = 1, AMOC = 0)
	cetaceans (T = 0, S = 0, AMOC = 0)
	Likelihood (Very likely = 3, Possible = 2, Unlikely = 1, Not Assessed = 0)
	zooplankton (T = 3, S = 3, AMOC = 2)
	<i>Calanus</i> life stages (T = 3, S = 3, AMOC = 2)
	demersal fisheries (T = 3, S = 3, AMOC = 2)
	cetaceans (T = 3, S = 3, AMOC = 2)
	Score for T (Consequence x Likelihood)
	zooplankton = 9
	<i>Calanus</i> life stages = 6
	demersal fisheries = 3
	cetaceans = 0
	Mean score for T overall = 4.5

	Score for S (Consequence x Likelihood)
	zooplankton = 6
	<i>Calanus</i> life stages = 3
	demersal fisheries = 3
	cetaceans = 0
	Mean score for S overall = 3
	Score for AMOC (Consequence x Likelihood)
	zooplankton = 0
	<i>Calanus</i> life stages = 0
	demersal fisheries = 0
	cetaceans = 0
	Mean score for AMOC overall = 0
	Combined score for T, S, AMOC changes
	zooplankton = 5
	<i>Calanus</i> life stages = 3
	demersal fisheries = 2
	cetaceans = 0
	Total mean score for Study Region = 2.5

Supplementary Material 2: Post hoc evaluation of forcing environmental variables not assessed by expert analysts in *Deliverable 3.2*

Study Region 4: Nova Scotia Slope

Summary of Deliverable 1.2 relevant for Study Region 4

The AMOC strength at 57°N calculated in VIKING20X and presented in D1.2 can be used to inform results from study region 4. At 57°N, there is no statistically significant linear trend in the strength of the AMOC found between 1980 and present, despite persistent decline in the strength of the AMOC being modelled since the late 1990s. In addition, forecasts predict a continuous decline in the strength of the AMOC, but this decline is not found to be statistically significant.

Following *Deliverable 1.2*, five water masses interact within study region 4: the Shelf Break Jet Water (SBJW), the Eastern North Atlantic Central Water (ENACW), the upper North Atlantic Deep Water (uNADW), the Lower North Atlantic Deep Water (LNADW) and the Northeast Atlantic Bottom Water (NEABW). Please refer to [Table S-1](#) in this Supplementary Material for a succinct overview of changes modelled for each water mass (VIKING20X hindcasts over 1980-2019 and forecasts over 2019-2070; reproduced from [Tables D1](#) and [F1](#) in the appendix of *Deliverable 1.2*).

Table S-1: Linear trends fitted to VIKING20X hindcasts and forecasts of temperature and salinity for the five water masses present in study region 4. Numbers in bold show significant trends.

Water mass	Hindcast temperature trend (°C decade ⁻¹)	Hindcast salinity trend (g kg ⁻¹ decade ⁻¹)	Forecast temperature trend (°C decade ⁻¹)	Forecast salinity trend (g kg ⁻¹ decade ⁻¹)
SBJW	+0.50	+0.0094	+0.42	+0.123
ENACW	+0.06	+0.005	+0.06	+0.023
uNADW	+0.04	+0.003	-0.08	-0.017
LNADW	+0.05	+0.009	+0.02	+0.002
NEABW	+0.01	+0.001	-0.06	-0.006

Linking AMOC strength to shifts to biological time series

No statistically significant changes in the strength of the AMOC modelled in VIKING20X was found at 57°N, but a change in AMOC strength was noted in the late 1990s. This does not, however, coincide with the breakpoint detected by statistical analyses reported in *Deliverable 3.2* in the biological datasets from Study Region 4 (zooplankton data: 2008 and 2014; demersal fish data: 1996 and 2012).

Linking changes in water mass properties (temperature/salinity) to biological time series

Analysis of outputs from the Bedford Institute of Oceanography North Atlantic Model revealed a significant increase in surface water temperatures and salinities especially in the later years of the time series. This is consistent with the breakpoints detected in both the zooplankton and demersal fish datasets. Further analysis of the ecological traits of zooplankton and demersal fish species increasing over time in study region 4 revealed that some warmer-water taxa are becoming more prevalent. With surface temperature and salinity predicted to further increase by 2070, it is therefore expected that the changes detected in both ecological compartments will continue in the future. Therefore, T and S were considered in *Deliverable 3.2* and subsequently used to assign scores in *Deliverable 3.3*.

Summary of deliverable 1.2 relevant for study region 5

The AMOC strength at 26°N calculated in VIKING20X and presented in *Deliverable 1.2* can be used to inform results from study region 5. At 26°N, no significant linear trend of the strength of the AMOC could be detected but an increase between 1980 and the mid-1990s was observed followed by a decline to present time. The AMOC strength is then predicted to continue to decrease but no clear statistically significant trend was identified.

Following *Deliverable 1.2*, seven water masses interact within study region 5: the SubTropical Under Water (STUW), the Western North Atlantic Central Water (WNACW), the Eastern North Atlantic Central Water (ENACW), the Antarctic Intermediate Water (AAIW), the upper North Atlantic Deep Water (uNADW), the Lower North Atlantic Deep Water (LNADW) and the Northeast Atlantic Bottom Water (NEABW). Please refer to [Table S-2](#) for a succinct overview of changes modelled for each water mass (VIKING20X hindcasts over 1980-2019 and forecasts over 2019-2070; reproduced from [Tables D1](#) and [F1](#) in the appendix of *Deliverable 1.2*).

Table S-2: Linear trends fitted to VIKING20X hindcasts and forecasts of temperature and salinity for the five water masses present in study region 5. Numbers in bold show significant trends.

Water mass	Hindcast temperature trend (°C decade ⁻¹)	Hindcast salinity trend (g kg ⁻¹ decade ⁻¹)	Forecast temperature trend (°C decade ⁻¹)	Forecast salinity trend (g kg ⁻¹ decade ⁻¹)
STUW	+0.02	+0.006	+0.21	+0.076
WNACW	-0.11	-0.031	+0.10	+0.035
ENACW	-0.11	-0.031	+0.01	+0.002
AAIW	-0.22	-0.038	-	-
uNADW	-0.08	-0.015	-0.06	-0.015
LNADW	0.00	+0.002	+0.02	+0.002
NEABW	0.00	0.000	-0.03	-0.004

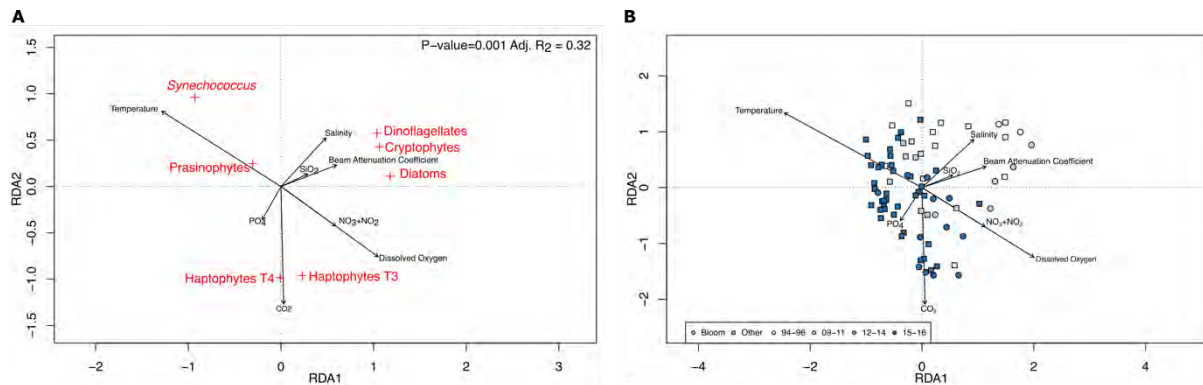
Linking AMOC strength to shifts to ecological time series

No statistically significant changes in the strength of the AMOC modelled in VIKING20X was found at 26°N but a change in AMOC strength was noted in the mid-1990s. This does not, however, coincide with the breakpoint detected in the biological datasets from study region 5 (phytoplankton data: 2004; zooplankton data: 2006 and 2012) and therefore experts did not assess impacts of AMOC for *Deliverable 3.2*.

Linking changes in water mass properties (temperature/salinity) to ecological time series

Strong increases in surface temperature and salinity, while not significant when modelled through VIKING20X, are known to have occurred at BATS (through measured data, see Bates and Johnson, 2020). This could have caused a shift in phytoplankton and zooplankton community data in the later part of ecological time series. An RDA model with phytoplankton (derived from pigment concentrations) as a response variable and temperature, salinity, nutrient concentrations, CO₂ and dissolved oxygen concentrations as explanatory variables was performed to further establish the links between changes in phytoplankton community composition and environmental conditions ([Figure S-1](#)). The RDA model was statistically significant and revealed that temperature was the most important driver of change followed by CO₂ and dissolved oxygen concentrations. However, the RDA model only explained 32% of the phytoplankton variability over time, highlighting that other drivers at the moment unknown are also at

play. The zooplankton data are made up of 5 large size classes and lacks any taxonomical classification. Attempts to analyse the zooplankton data through RDA modelling did not reveal any significant trends, most likely due to the broad size categories used in the dataset but impacts of T and S were still assessed in *Deliverable 3.2* as experts working on the BATS data for nearly three decades understand the influence these variables can have on the pelagic ecosystems in this region.



Supplementary Material Figure S-1: RDA biplots with phytoplankton data derived from pigments as response matrix and environmental matrix as explanatory variables. (A) Species biplot. (B) 'Sites' (here time points) biplot. Reproduced from *Deliverable 3.2*.

Reference:

Bates, N. R. and Johnson, R. J. (2020). Acceleration of ocean warming, salinification, deoxygenation and acidification in the surface subtropical North Atlantic Ocean. *Communications Earth & Environment* 2020 1:1, 1(1), 1–12. <https://doi.org/10.1038/s43247-020-00030-5>

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