AtlantOS

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| **Deliverable number** | 8.16 |
| **Deliverable title** | Report on AtlantOS fitness to MSFD needs |
| **Description** | Assessment of impact of AtlantOS on North West Shelf state reanalyses. |
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| **Work Package title** | Societal benefits from observing/information systems |
| **Lead beneficiary** | Met Office |
| **Lead authors** | Rosa Barciela, Jonathan Tinker, Richard Wood (editor) |
| **Contributors** | |
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| **Comments** | |

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## Stakeholder engagement <u>relating to this task</u>*

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| **WHO are your most important stakeholders?** | ☐ Private company<br>If yes, is it an SME ☐ or a large company ☐?<br>☒ National governmental body<br>☐☒ International organization<br>☐ NGO<br>☐ others<br>Please give the name(s) of the stakeholder(s):<br>• ICES<br>• EEA<br>• Cefas<br>• CMEMS service providers |
| **WHERE is/are the company(ies) or organization(s) from?** | ☒ Your own country<br>☒ Another country in the EU<br>☐ Another country outside the EU<br>Please name the country(ies):<br>• UK<br>• International bodies based in Denmark<br>• CMEMS service providers (from several European countries) |
| **Is this deliverable a success story? If yes, why?**<br>**If not, why?** | ☒ Yes, because:<br>Specific priorities have been identified to develop the value chain between CMEMS and end users<br>Scientific insights have been gained into the possible impact of an improved Atlantic observing system on the quality of analyses of European regional seas (although further research, identified by our work, is needed to establish the full impact). |
| **Will this deliverable be used?**<br>**If yes, who will use it?**<br>**If not, why will it not be used?** | ☐ Yes, by CMEMS service providers, intermediate users and end users, in prioritising work to develop a strong value chain. |

**NOTE: This information is being collected for the following purposes:**

1. To make a list of all companies/organizations with which AtlantOS partners have had contact. This is important to demonstrate the extent of industry and public-sector collaboration in the obs community. Please note that we will only publish one aggregated list of companies and not mention specific partnerships.
2. To better report success stories from the AtlantOS community on how observing delivers concrete value to society.

*For ideas about relations with stakeholders you are invited to consult D10.5 Best Practices in Stakeholder Engagement, Data Dissemination and Exploitation.

**Executive Summary**

This report assesses the potential impact of the Atlantic Ocean observing system, in support of the Marine Strategy Framework Directive (MSFD) and fisheries planning. Our starting point is the use of regional reanalyses, which assimilate observations into an ocean model to produce a spatially and temporally complete and consistent estimate of the past ocean environmental state, constrained by the assimilated observations. Since the marine observational network is so sparse, such reanalyses are potentially a highly valuable tool to quantify and understand the marine environment in unobserved regions, and to put any variations or trends seen in the actual observations into a wider and longer term context.

For our testbed we use the Northwest European Shelf (NWS) reanalysis system produced and maintained by the Met Office in collaboration with partners at the National Oceanography Centre (NOC, UK), Plymouth Marine Laborartory (PML, UK) and Bundesamt für Seeschifffahrt und Hydrographie (BSH, Germany) and delivered freely through the Copernicus Marine Environment Monitoring Service (CMEMS). This provides ocean state estimates for physical and biogeochemical variables for the NWS region, covering the period 1992 to near present, using a model with a 7km mesh.

Our study includes two topics: Part 1 presents an evaluation of user needs for such reanalysis products, based on in-depth discussions with three major European stakeholders, while Part 2 presents a scientific study of the extent to which the open ocean Atlantic observing system can constrain reanalyses in the NWS region, by improving the lateral ocean boundary conditions for the NWS regional model. Part 2 draws on work in AtlantOS WP1 (Task 1.3, Deliverable 1.5) to assess the added value of potential new observing elements in constraining the open ocean state (and hence the open ocean boundary conditions for the NWS model).

*Part 1:*
User requirements were assessed through in-depth interviews with three user organisations, also involving the service providers, representing a range of interests in the use of CMEMS products for marine monitoring. These interviews revealed a number of specific interests of the users in particular variables and derived products, as well as opportunities for improving integration across existing European activities. Some wider priorities that emerged for the future included: achieving good integration of CMEMS data with GIS systems; documenting and where necessary improving consistency between different regional products; and development of communications channels between users and producers as uptake of the products increases. Details can be found in the main report.
It is important to stress that the development of the value chain from CMEMS production to a vibrant end user community requires continuing work at all points in the value chain: CMEMS producers, intermediate users and end users. The insights developed in this work will help all parties to focus their future development priorities towards this goal.

*Part 2:*
Here we consider the potential impact of the open ocean Atlantic observing system on the state of the NWS. We consider the direct impact of the open ocean through the lateral boundary conditions it provides to a regional model of the NWS. First we show that on interannual timescales variability in lateral boundary conditions has little impact on shelf seas temperature (which is controlled largely by atmospheric surface forcing), but does have some influence on salinity. We then draw on the results of AtlantOS Task 1.3 to assess the potential impact of an improved Argo float coverage on the NWS lateral boundary conditions. Because the Observing System Simulation Experiments (OSSEs) of Task 1.3 were relatively short in duration (2 model years), we only have information on timescales from daily up to seasonal. On these timescales the influence of the additional Argo observations on the NWS boundary conditions is small. It is expected that the influence of the observations will be greater on interannual timescales. Our results therefore suggest that there would be little influence from these Argo improvements on short timescale NWS analyses and forecasts. However the influence for longer timescale applications is expected to be greater, and the following are

identified as future research priorities to assess this: (i) longer OSSE experiments to cover climate timescales; (ii) coupled data assimilation experiments to assess the indirect impact of the ocean observations on the NWS through improving the associated atmospheric circulation; (iii) OSSE experiments with deliberately biased ‘truth’ models to better represent biases between the underlying model and the real world; (iv) further development of data assimilation schemes which capture the remote influence of boundary observations throughout the basin.

Some of these results are now published in the peer-reviewed literature (Tinker et al 2018), with a second publication in preparation (Tinker et al., in prep.).

# Part 1: User needs

## 1.1 Introduction

In addition to scientific research (Part 2), we carried out focused discussions with targeted, and potential, users of the CMEMS reanalysis products, to explore the key requirements of such products from a user perspective. These users were the International Council for Exploration of the Sea (ICES, based in Copenhagen), European Environment Agency (EEA, also based in Copenhagen) and the Centre for Environment, Fisheries and Aquaculture Science (Cefas, based in the U.K.). They were specifically chosen because of their different remits and responsibilities for fisheries management and Marine Strategy Framework Directive (MSFD) monitoring and compliance, at national and international level. The MSFD is particularly relevant as it requires EU Member States to take the necessary measures to achieve, monitor and maintain good marine environmental status.

The purpose of the user engagement was to gain an understanding:

- (By the AtlantOS project and CMEMS) of specific user requirements and how CMEMS products can help deliver them, as well as any barriers to overcome.
- (By the users) of what value may be added and how users can contribute to the research and product development cycle.
- (By all) of the opportunities the current CMEMS products bring as well as opportunities for co-developing future products and services.

This report details the context, and summarises the outcomes, of the discussions held over the course of three meetings, during 2017. CMEMS, ICEA and EEA participated in joint discussions in Copenhagen (November 2017) in order to develop joint understanding of the priorities between users and producers.

## 1.2 Remit

This report cannot cover every aspect of user engagement. We therefore framed the discussions around a series of questions in order to make the scope of the discussions, and the expectations of those involved in them, comprehensible and manageable. We also wanted to ensure the outcomes of the discussions were clear and the recommendations made are achievable.

The discussions were structured around a series of questions, and we summarise the results here under the following headings:

1. *How do the CMEMS products meet your requirements? How are they being used/do you plan to use them?*
2. *What is the value, as well as the limitations, of such products?*
3. *How would you like the products and service to develop in the future?*

## 1.3 Summary of discussions

### *1.3.1 International Council for the Exploration of the Sea (ICES)*

In 2014, CMEMS won a bid, in response to an ICES Invitation To Tender (ITT) issued in 2014, offering to provide a number of oceanographic products. Variables provided are: sea surface temperature, salinity and water column stratification.

1. ***How do the CMEMS products meet your requirements? How are they being used/do you plan to use them?***

ICES envisaged the CMEMS products would underpin the development of bespoke, in-house web tools, including an ICES Web Feature Service (WFS)/Web Map Service (WMS) that would routinely, and automatically, query ICES databases and platforms. One such example is the Transparent Assessment Framework (TAF), a framework to organize data, methods, and results used in ICES assessments, so they are easy to reference and re-run. The TAF is an online archive of final assessment for each year, for all stock categories. All data input and outputs are linked to existing or upcoming ICES data services. This WFS is an ICES flagship and underpins the advisory role of ICES in the provision of ecosystem overviews for policy makers.

2. ***What is the value, as well as the limitations, of such products?***

The integration of the CMEMS products in the ICES advisory chain is where the CMEMS products bring the highest value. This is because ICES is a provider of scientific advice in the North Atlantic, particularly in terms of the exploitation and stewardship of the marine ecosystem and marine living resources. Within this role, it has developed integrated ecosystem advice at regional level which is used by managers, policy developers and interested stakeholders. As part of these activities, ICES has constructed “Ecosystem Overviews” which describe the trends in pressures and state of regional ecosystems. ICES is making this advice operational, which entails having a clearly defined business process that outlines the roles, operators, methodologies, timetables and agreed deliveries of services/products that constitute the advice mechanism. These advice processes require regular inputs of monitoring information on the oceanography and hydrology of the regions, which could be well served by the CMEMS.

Some steps are still needed to achieve full integration of CMEMS data into the ICES products. These include operational integration of data flows from CMEMS into the GIS-based systems used by ICES, and a ‘seamless’ synthesis of the various CMEMS regional and global products into a self-consistent dataset for the North Atlantic domain.

3. ***How would you like the products/service to evolve in the future?***

ICES has a well-defined list of priority requirements, which are:

- New parameters: pH, Arctic ice cover, heat and oxygen content.

  ICES policy role has recently expanded beyond fisheries to include other science and policy requirements, including MSFD. The split in responsibilities currently stands as 60% fisheries, 40% MSFD. As such, ICES has also broader requirements for new data products such as these.

- Environmental indicators (derived products)

  Top ICES priorities are:
  - Monthly mean SST and near-bottom temperature and their seasonal anomalies.
  - Monthly mean SSS and near-bottom salinity and their seasonal anomalies.
  - Monthly mean stratification
  - Long time-series trend analysis ready to be used on the ICES website (based on monthly/other averaged data) of temperature, salinity and stratification for ICES ecoregions

- Monthly mean of Artic ice-cover (lower priority).

The CMEMS regions of interests are the NWS & IBI, then BAL & ARC (lower priority). This request is to be further clarified by ICES via its Working Group on Operational Oceanography for Fisheries and the Environment (WGOOFE) and Working Group on Oceanic Hydrography (WGOH).

Further areas of importance to ICES for future development include:

- Develop consistency and 'seamlessness' of environmental assessments for the whole North Atlantic region across the CMEMS global and regional Marine Forecasting Centres.
- Further development of the user support function to support complex user requirements
- Increased information on characteristics of data products
- Consultation and possibly co-development of derived products (e.g. Ocean Monitoring Indicators)
- Development of formal and informal mechanisms of engagement between service providers and users.

These areas are likely to require work by a mix of providers, users, and the 'intermediate user' sector.

### 1.3.2 *European Environment Agency (EEA)*

Discussions with the EEA took place because of their role in coordinating and sharing information that supports the European-wide implementation of the Marine Strategy Framework Directive (MSFD). For this purpose, the EEA, in collaboration with Eurostat and other European Commission partners (DG-ENV, DG-JRC), is currently developing the WISE-Marine portal (http://water.europa.eu/marine) and have invested in required associated infrastructure for sharing information on the marine environment across European regions and member states. Their aim is to gather all available information collated through the MSFD process, which includes characterising the marine environment, and publicising all this information widely.

1. ***How do the CMEMS products meet your requirements? How are they being used/do you plan to use them?***

At the time of this meeting, in November 2017, the EEA were not exploiting any CMEMS products. This meeting was convened in order to explore the potential opportunities that CMEMS could bring, within the specific context of contributing to the WISE-marine portal, as outlined earlier.

2. ***What is the* value*, as well as the limitations, of such products?***

The EEA plans to test the inclusion of CMEMS modelling global temperature products and, subject to a successful outcome of the trial, global salinity and chlorophyll products. Other products of interest, in addition to existing salinity and chlorophyll-a, are ice and waves.

The WISE-Marine portal is being built underpinned by GIS layers and will include a GIS map viewer. Therefore, full GIS interfacing and reliable performance are fundamental to harnessing CMEMS data.

3. ***How would you like the products/service to evolve in the future?***

Specific requirements include:

- Ice coverage.
- Waves.

Interest in derived products includes:

- Long time-series trend analysis of temperature, salinity and stratification.
- Indices of temperature, acidification, heat content, oxygen content.
- The EEA would welcome the opportunity to be consulted on the co-development of products of interest, such as Ocean Monitoring Indicators (OMIs)

These areas are likely to require work by a mix of providers, users, and the 'intermediate user' sector.

### *1.3.3 Centre for Environment, Fisheries and Aquaculture Science (CEFAS)*

Cefas is a marine science and technology centre in the UK. Their role includes the development and assessment of marine ecosystem indicators in support of the Oslo and Paris Convention for the protection and conservation of the North-East Atlantic (OSPAR) and MSFD. Such assessments provide an important evidence base for multiple stakeholders, including governments and policy makers, and are underpinned by multiple data sources and products via the CefMAT web tool.

1. ***How do the CMEMS products meet your requirements? How are they being used/do you plan to use them?***

Cefas are currently developing a marine web tool called CefMAT. It is a multi-platform data tool designed to support the assessment of MSFD and OSPAR indicators. Through funding via one of CMEMS user demonstration projects, this tool is being further developed to integrate CMEMS products and to also quantify the impact of these additional data on the evaluation of MSFD descriptors, with a particular focus on Descriptor 1 (biological diversity) and Descriptor 2 (non-indigenous species).

The CMEMS products already embedded in CefMAT are: chlorophyll-a, nitrogen, phosphorus, dissolved oxygen, average net primary productivity and average light attenuation radiative flux.

2. ***What is the value, as well as the limitations, of such products?***

It is envisaged CMEMS satellite and modelling products will add value to the tool by addressing the spatial and temporal limitations of *in situ* data. Therefore, CMEMS products will contribute to the provision of better informed marine assessments and evidence. There is also potential to use the data to improve emergency response prediction, fish modelling and overall assessments of hydrographical conditions, water quality, eutrophication, biodiversity and marine food webs.

Cefas have in the past used alternative data sets, such as NCEP reanalyses and the NOAA climate portal, which provide additional downstream processing functionally such as data subset interrogation, inter-operable data extraction, on-the-fly data analysis, visualisation and reporting. Development of such downstream processing for CMEMS data would increase the ease with which the value of the CMEMS data can be extracted.

***3. How would you like the products/service to evolve in the future?***

- A wish list of additional parameters includes: sea level, water column stratification, water circulation, pH, turbidity.

- Cefas would like an annual update to the reanalysis products. At the time of these discussions some products were longer behind real time than others. This has since been addressed by CMEMS.

- Additionally, climate products would be a valuable addition to the CMEMS portfolio. This is because environmental assessments, for OSPAR and MSFD, require a marine climate outlook (may best be delivered in collaboration with the Copernicus Climate Change Service).

- As operational use grows more complex the requirements will increase for routine lines of communication regarding upcoming service disruptions or retirement/replacement of existing products.

These areas are likely to require work by a mix of providers, users, and the 'intermediate user' sector.

## 1.4 Conclusions

Focused discussions with targeted, and potential, users of the CMEMS reanalysis products have provided an insight into: (i) the users' detailed requirements, (ii) how the products would be/are being used, (iii) the actual and perceived barriers to future uptake, and (iv) the opportunities to assist the future evolution of CMEMS products and a vibrant user base.

The user engagement task organically grew into a wider involvement of users with service producers and has already yielded tangible benefits, including:

- Greater clarity on current and future requirements, and understanding of how the products will be used and for what purpose, feeding into thinking on future product development (e.g. Ocean Monitoring Indicators).
- Plans to investigate possible integration of CMEMS global products into the EEA's WISE-marine portal. This would connect two strategically- and centrally-funded European programmes, therefore expanding on their individual outreach and impact.

Specific themes that emerged from the consultation included:

- Integration of CMEMS data with WMS and WFS technologies, which are also fundamental to GIS developers, is a key area to allow uptake of products.

- Documented (and if necessary improved) consistency between different regional products (including global) is important for some users whose domains of interest span more than one CMEMS region.

- Continuous development of communications channels between producers and users (intermediate and end-user) will be important as the service uptake develops. This will include operational matters (e.g. notice of service disruption, replacement of products), user support, and input to derived products such as Ocean Monitoring Indicators. A user forum was one idea suggested to facilitate two-way communication.

We stress again that the development of the value chain from CMEMS production to a vibrant end user community requires continuing work at all points in the value chain: CMEMS producers, intermediate users and end users. The insights developed in this work will help all parties to focus their future development priorities towards this goal.

# Part 2: Influence of the Atlantic Observing System on the Northwest European Shelf Seas

## 2.1 Motivation and overall plan

Environmental quality indicators for MSFD (Marine Strategic Framework Directive) require the best possible estimates of the three-dimensional state of the shelf seas, now and in the recent past (reanalyses). In this pilot project we investigate the value of AtlantOS observations in improving physical and biogeochemical reanalyses of the North West European Shelf, using the North West European Shelf (NWS) regional reanalysis system of the Copernicus Marine Service. In WP1, the influence of various Atlantic Ocean observation types on reanalyses of the open ocean state was assessed (AtlantOS deliverable D1.5). Here, we investigate the influence of the open ocean on the shelf seas and consider how the open ocean conditions derived from these studies would affect the conditions on the NWS. This illustrates the possible impact of new observations in constraining the NWS state, and potentially leads to more confident attribution of the causes of observed changes on the shelf, and to improved extended range (seasonal) forecasts.

## 2.2 Scientific questions

In this work package, we investigate how improvements to the Atlantic Observing system might impact model simulations of the North-West European Shelf seas (NWS). We note the NWS is a broad, shallow shelf sea, which allows significant interaction with the overlying atmosphere. Furthermore, we note that the NWS is bounded by a steep continental shelf break, and a strong, northward flowing, slope current (~2Sv), both of which act to reduce exchange between the NWS and the open ocean – the NWS is considered a quasi-isolated basin (Wakelin *et al.* 2009)

We consider the primary mechanism by which an improved an Atlantic Observing system can affect the NWS – through the lateral ocean boundary conditions. We do not consider the secondary route, by which an improved Atlantic Observing system would improve the modelling of the Atlantic, in turn altering the overlying atmosphere, and entering the NWS model domain through the atmospheric surface boundary conditions. A tertiary route (with atmosphere changes altering the riverine input) is also neglected here. We focus on the inter-annual timescale, so look how year-to-year variability in the Atlantic is related to year-to-year variability on the NWS.

This research topic is framed as:

> *If we improve the Atlantic Observing system through additional open ocean observations, will model simulations (forecasts and reanalyses) of the NWS improve?*

In order to address this, we have identified the following of scientific questions.

Q1: What is the relationship between the NWS and its ocean Lateral Boundary Conditions (LBCs)?

Q2: How much of the NWS variance is related to the LBCs?

Q3: Given the AtlantOS observing system will lead to differences to the ocean state in the vicinity of the NWS, how large are these differences compared to the year-to-year differences investigated above?

Each of these scientific questions is addressed by separate scientific analysis, which is described below.

### 2.2.1 Q1: What is the relationship between the NWS and its boundary conditions?

In order to study the relationships between the NWS and its boundary conditions, we performed a correlative study (Tinker et al. 2018). In a NWS reanalysis, we investigated relationships between the state of the NWS, and its atmospheric, oceanic and riverine boundary conditions. The NWS was broken into a number of regions, and spatially averaged time-series of Sea-Surface and Near-Bed Temperature and Salinity (SST, NBT, SSS and NBS respectively) were calculated for each region. Time-series of the atmospheric and riverine conditions in the same regions were also calculated, as were the oceanic conditions around the NWS boundary, using appropriate region masks. Significant correlations between the boundary conditions and the NWS can suggest a relationship, especially when there is a physically understandable pattern to the correlations.

We find that NWS surface temperature is strongly correlated to atmospheric boundary conditions. Often, the NWS temperature is also strongly correlated with the lateral boundary oceanic temperature (Figure 2.1a,c), but this is not thought to be a causal link, and simply reflects common large scale temperature anomalies in the atmospheric conditions. The broad shallow nature of the NWS allows the shelf waters to equilibrate with the atmospheric conditions, and so to “forget” the oceanic temperatures.

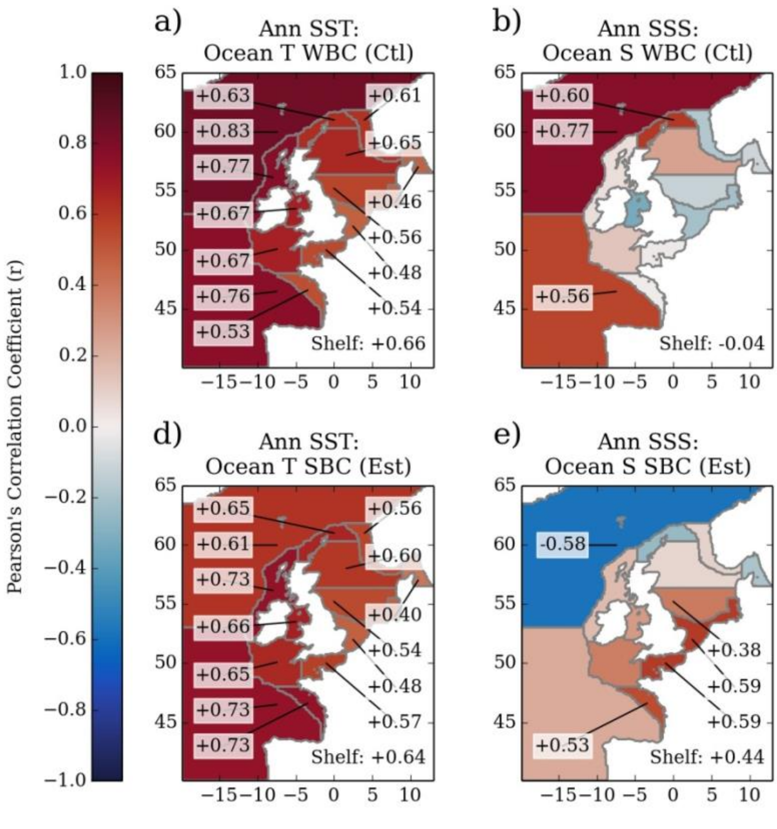


**Figure 2.1 Correlation maps between time series (annual mean unless stated otherwise) of model forcings and shelf response. Insignificant correlations (at the 95 % confidence level) are not given. The individual panels relate the shelf response to the forcing: (a) SST and oceanic temperature at the west of the domain (western boundary–surface_central); (b) SSS and oceanic salinity at the west of the domain (western boundary–surface_central); (d) SST and oceanic temperature at the south of the domain (southern boundary–surface_east); (e) SSS and oceanic salinity at the south of the domain (southern boundary–surface_east). The different boundary regions are defined in Table 2.1. The correlation maps given are not necessarily the strongest correlations, but have been selected to illustrate the observed patterns consistently.**

Surface salinity responds to the atmospheric conditions on a slower time scale than temperature, and so the variability in the oceanic boundary conditions can persist longer. When looking at correlation patterns between the ocean LBCs and the NWS SSS, we find that the correlations with the salinity along the eastern portion (east of 12°W) of southern boundary propagate into the NWS through the Celtic Sea, and into the Irish and English Channel (Figure 2.1e). When looking at the salinity of the western boundaries (between 52.5°N and 58°N), the salinity correlates with the Atlantic oceanic region and this persists through the Shetland shelf region, towards the Northern North Sea (Figure 2.1b).

This analysis shows where the SSS on the NWS correlates with the salinity on the boundaries in the reanalysis (1983-2013). This is an important step, as it identifies a relationship between the two, and even suggests that the variance of the boundaries induces the salinity variability on the NWS. However, it does not prove that this is a causal relationship. As for temperature, the correlations between the NWS SST and lateral oceanic temperature may reflect common large scale atmospheric drivers.

In order to prove that the oceanic variance is an important component of the NWS variance, and so that changes in estimates of the ocean state can affect the NWS, sensitivity tests are required.

### 2.2.2 Q2: How much of the NWS variance is related to the OBCs?

We have investigated drivers of interannual sea-level variability on the NWS. Results are being prepared for a peer-reviewed publication (Tinker et al. in preparation). We use an updated version of the reanalysis shelf seas model to downscale a 'present-day control' (PDCtrl) climate simulation of HadGEM3-GC3.0 (Williams et al. 2018), a precursor to the Met Office Hadley Centre's CMIP6 model (sixth phase of the Coupled-Model Intercomparison Project). This model run has fixed, year-2000 greenhouse gases and is used to produce an estimate of unforced natural variability in the atmosphere and global ocean. We extract boundary conditions from a 90-year segment of this run to drive the Met Office's operational configuration of the NEMO model for the NWS region, known as CO6. This run is used as an estimate of the natural variability of the NWS marine environment and its projection onto regional sea level. We also ran sensitivity experiments, holding the atmospheric boundary conditions to a seasonally varying climatology (PDCtrlAtmos) to quantify the NWS variance associated with variability in the oceanic boundary conditions, and holding the oceanic boundary conditions to a climatology (PDCtrlOcean) to quantify the NWS variability associated with the atmospheric boundary conditions. All of these simulations were run with a seasonally varying climatological riverine and Baltic Sea boundary conditions.

These sensitivity experiments allow us to establish the relationship between the variance of the NWS and of the oceanic and atmospheric boundary conditions. Initially, we consider the Fraction of Variance (Roberts *et al.* 2016) for the main present day control simulation, and for the sensitivity experiments. Figure 2.2 (upper) shows the fraction of variance of NWS SST that is associated with variance in  the open ocean boundary condition. The CO6 domain includes the NWS shelf seas region as well as a substantial area of the North-East Atlantic deep ocean, to the west of the shelf break. As suggested by Tinker *et al.* (2018), the fraction of SST variance on the shelf that is associated with the ocean lateral boundary condidition is negligible – the oceanic variance accounts for ~0% of the variance, and the atmospheric variance accounts for ~100%.

When looking at NWS salinity (Figure 2.2 lower) the oceanic variance plays a greater role, although the atmospheric variance still dominates. In the open ocean part of the domain, the oceanic variance is the dominant source of SSS variance, but the shelf break is a clear barrier. The oceanic variance penetrates onto the NWS across the Shetland Shelf region, and into the northern North Sea. The Dooley current (roughly eastward North Sea current at ~58°N) acts as a secondary barrier, and there is much less oceanic variance south of this. An important pathway into the NWS is around Scotland, however, this region (as with all coastal regions) has significant climatological river input, which would dilute both atmospheric and oceanic variability. The Oceanic variance also enters into the Celtic Sea, and towards the Irish Sea and English Channel.

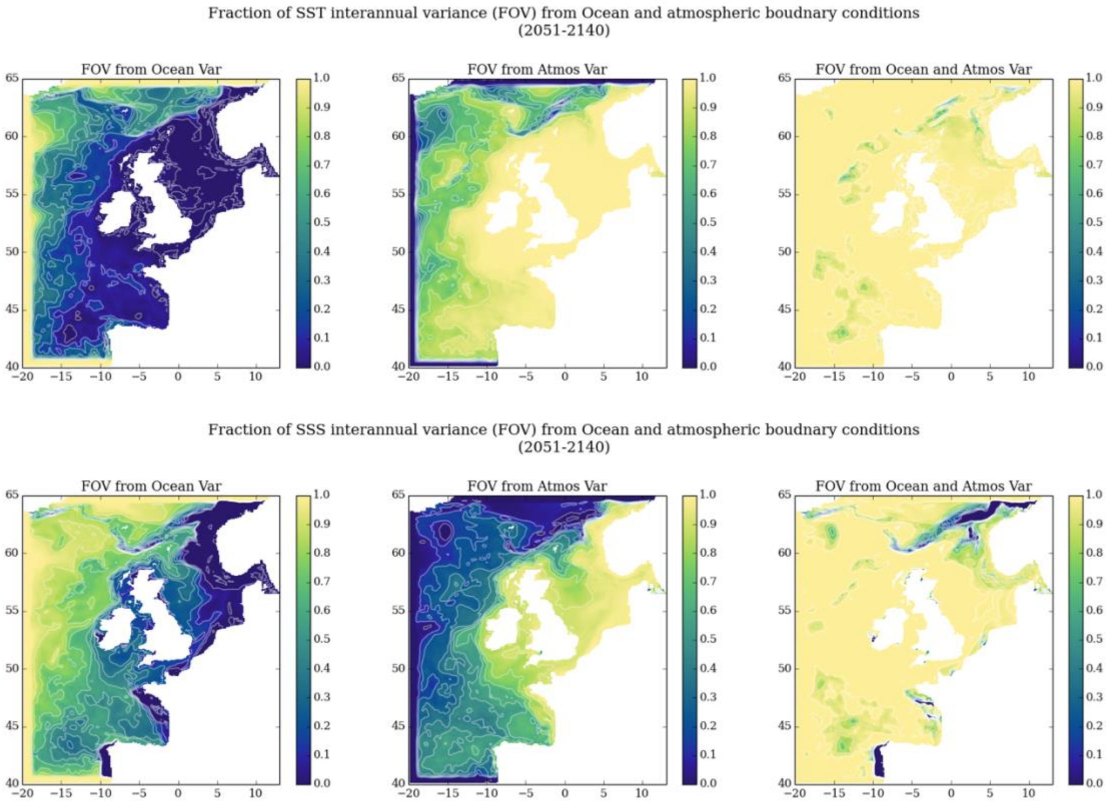


**Figure 2.2 The Fraction of SST (upper row) and SSS (lower row) Variance associated with the oceanic variance at the lateral boundary conditions (left column) and atmospheric variance in the surface boundary conditions, according to the Roberts *et al.* (2016) methodology. The right hand column is the sum of the left and central panels, to show where there are missing terms (including co-variance and non-linearity).**

From these sensitivity experiments, we can show that the temperature variability in the ocean LBCs does not propagate onto the NWS, while oceanic salinity variability plays a minor role in a limited area. In order to evaluate the influence of possible new open Atlantic observations on the NWS, we need to quantify that influence relative to interannual variability in the boundary conditions.

### 2.2.3 Q3: Given the AtlantOS observing system will lead to differences to the ocean state in the vicinity of the NWS, how large are these differences compared to the year-to-year differences investigated above?

AtlantOSWP1.3 ran Observations System Simulation Experiments (OSSE) to quantify the impact improving the Atlantic Observing System would have on the world ocean. They ran a number of 2 year experiments with a global ocean model assimilating simulated observations (sampled from an independent ‘Nature Run’) under different potential Atlantic Observing systems. Success is defined as when the simulated observations from the Nature Run are assimilated into a different model, the model solution becomes close to the Nature Run.

Here we compare two model runs of the Met Office FOAM system, BB and WBC. BB (Backbone) simulates the current (or near future) Atlantic Observing system, while WBC represents the same observing system with additional Argo floats deployed in the Western Boundary Currents and along the equator. The WBC observing system was found to improve the estimated Atlantic Ocean state (measured by RMS errors against the Nature Run) throughout the Atlantic, and this experiment was chosen in consultation with the scientists performing the OSSE experiments as the one most likely to produce an impact. For details of the OSSE and the above analysis see Appendix A of AtlantOS Deliverable D1.5.

Here we extend the analysis of D1.5 to look in more detail at the impact of the WBC observing array on the global model solution in the vicinity of the domain boundary of the CO6 regional model. We note that the BB run already has rather low errors against the Nature Run in this region, so the scope for improvement from extra observations is limited. To analyse the results, we adopt the approach of Tinker *et al.* (2018), and create spatially averaged time series for comparison. Firstly, the BB and WBC (three-dimensional) temperature and salinity and sea surface height are interpolated onto the open boundary grid boxes of the CO6 model grid. The upper 30m of the temperature and salinity data are averaged (weighted by model layer thickness). The three (Atlantic facing) open boundaries are spatially averaged into 8 time-series (see Table 2.1 for details). Example timeseries from the southern portion of the Western Boundary are shown in Figure 2.32.3. We call these timeseries AtlantOS_BB_BC and AtlantOS_WBC_BC respectively. The OSSE experiments were run for two years, with daily output, whereas our sensitivity experiments reported above were run for 80 years, and the monthly mean output was analysed. Care must be taken when comparing the variance of two datasets with different sampling frequency, as the higher frequency variance may dominate. When considering the results, we comment on the potential impact of this.

| **Open Lateral Boundary** | **Section** | **Spatial criteria** |
|---|---|---|
| Northern Boundary | West | Longitude < 10°W |
| Northern Boundary | Central | 10°W > Longitude > 2.5°E |
| Northern Boundary | East | Longitude > 2.5°E |
| Western Boundary | South | Latitude < 52.5°N |
| Western Boundary | Central | 52.5°N > Latitude > 58°N |
| Western Boundary | North | Latitude > 58°N |
| Southern Boundary | West | Longitude < 12°W |
| Southern Boundary | East | Longitude > 12°W |

**Table 2.1 Description of lateral boundary spatial mean time-series. Global ocean model data initially nearest-neighbour interpolated onto the open boundary grid boxes of the CO6 domain. Note upper 30 metre depth averaging is applied to the 3D Temperature and Salinity fields.**

$T_{(30)}$ $S_{(30)}$ SSH

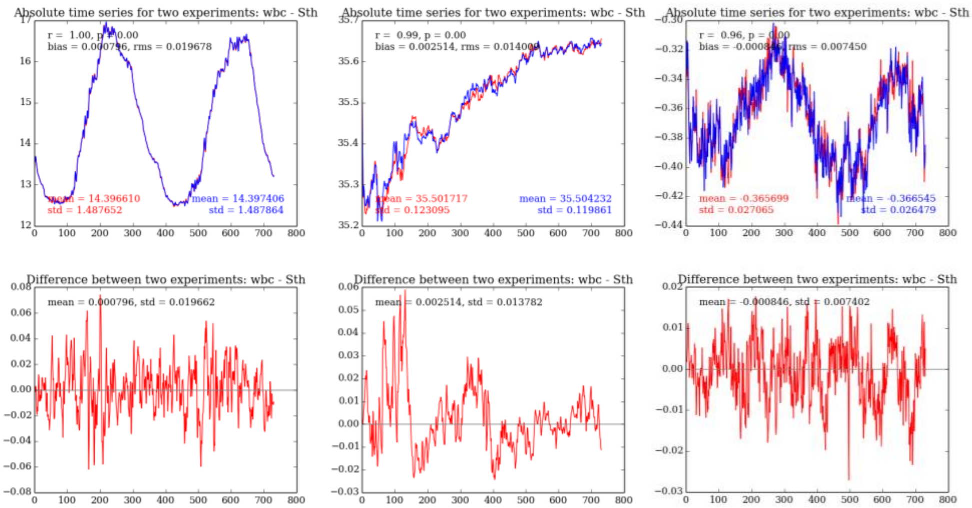


**Figure 2.3 Example spatial mean time-series from the AtlantOS OSE simulation (AtlantOS_BB_BC and AtlantOS_WBC_BC) from the southern portion of the western boundary (south of 52.5°N). Upper row are the absolute time series (AtlantOS_BB_BC: red, AtlantOS_WBC_BC: blue), and the lower panels are the anomaly AtlantOS_WBC_BC -AtlantOS_BB_BC). The left-hand and central panels are the upper 30m, depth-averaged Temperature and Salinity respectively, while the right-hand panel is the sea surface height.**

Statistical summaries of the differences between the WBC run and the BB run for all the CO6 boundary regions are presented in Table . The time-series are very similar. All have significant correlations ($p<0.01$) greater than $r > 0.95$. The tables also show a ‘relative bias’, obtained by dividing the WBC bias by the WBC standard deviation, and a ‘relative standard deviation’, obtained by dividing the WBC standard deviation by the BB standard deviation.

All variables have very small mean biases and rms (Temperature: $|bias| < 0.01$°C, rms $<0.13$°C; salinity ($|bias|<0.012$ psu, rms $< 0.033$ psu, ssh: $|bias| < 0.003$ m, rms $< 0.013$ m). Furthermore the relative bias is small, indicating that the difference between the two experiments is small compared with the variability of the timeseries itself (dominated by the seasonal cycle for temperature and SSH, and possibly by model drift for salinity), and the relative standard deviation is very close to 1.

| Temperature (°C) | Mean Bias (WBC-BB) (°C) | RMS (°C) | Relative bias bias(WBC) / std(WBC) | Relative std dev std(BB) / std(WBC) |
|---|---|---|---|---|
| Western BC:Sth | 0.000796 | 0.019678 | 0.000535 | 0.999858 |
| Western BC:Ctl | 0.000576 | 0.035615 | 0.000432 | 0.995618 |
| Western BC:Wst | -0.00108 | 0.021203 | -0.00078 | 1.000019 |
| Northern BC:Wst | -0.00667 | 0.082824 | -0.00444 | 0.993623 |
| Northern BC:Ctl | -0.00546 | 0.042139 | -0.00272 | 1.003333 |
| Northern BC:Est | 0.003162 | 0.027462 | 0.001498 | 0.994849 |
| Southern BC:Wst | -0.00102 | 0.028298 | -0.0005 | 1.002804 |
| Southern BC:Est | -0.00728 | 0.054283 | -0.00405 | 1.001853 |

**Table 2.2 Statistical summary of the temperature boundary conditions from the two AtlantOS WP1.3 OSSE experiments.**

| Salinity (psu) | Mean Bias (WBC-BB) (psu) | RMS (psu) | Relative bias Bias / std(WBS) | Relative std dev std(BB) / std(WBC) |
|---|---:|---:|---:|---:|
| Western BC:Sth | 0.002514 | 0.014009 | 0.020978 | 1.026975 |
| Western BC:Ctl | -0.00017 | 0.015227 | -0.00099 | 0.973715 |
| Western BC:Wst | -0.00113 | 0.006498 | -0.01219 | 1.007641 |
| Northern BC:Wst | -0.00648 | 0.032298 | -0.02846 | 0.95939 |
| Northern BC:Ctl | 0.004467 | 0.015041 | 0.077731 | 0.977935 |
| Northern BC:Est | -0.00535 | 0.018447 | -0.0224 | 1.00514 |
| Southern BC:Wst | -0.00436 | 0.01323 | -0.04844 | 0.96697 |
| Southern BC:Est | -0.01175 | 0.030717 | -0.06336 | 1.016675 |

**Table 2.3 Statistical summary of the salinity boundary conditions from the two AtlantOS WP1.3 OSSE experiments.**

| **Sea-surface Height (m)** | **Mean Bias (WBC-BB) (m)** | **RMS (m)** | **Relative bias Bias / std(WBS)** | **Relative std dev sd(BB) / sd(WBC)** |
|---|---|---|---|---|
| Western BC:Sth | -0.00085 | 0.00745 | -0.03194 | 1.022137 |
| Western BC:Ctl | 0.000651 | 0.012971 | 0.014941 | 0.916144 |
| Western BC:Wst | 0.001209 | 0.009018 | 0.029253 | 0.965766 |
| Northern BC:Wst | 0.002903 | 0.009271 | 0.045279 | 0.975949 |
| Northern BC:Ctl | 0.000919 | 0.003738 | 0.019243 | 0.989494 |
| Northern BC:Est | 0.002478 | 0.007847 | 0.046291 | 0.982871 |
| Southern BC:Wst | 0.000464 | 0.004808 | 0.013164 | 0.980783 |
| Southern BC:Est | 0.001293 | 0.00776 | 0.047562 | 0.977496 |

**Table 2.4 Statistical summary of the sea-surface height boundary conditions from the two AtlantOS WP1.3 OSSE experiments.**

These results suggest that the impact of the additional Argo observations on the oceanic conditions around the NWS is very small compared to the difference in the oceanic boundary conditions used in the sensitivity experiments of Section 2.2.2 (PDCtrl and PDCtrlOcean). However this is not a clean comparison since the variability in the two-year OSSEs is dominated by the seasonal cycle and higher frequencies, whereas the experiments of Section 2.2.2 focus on interannual and longer timescales. It is on these longer timescales that we would expect the open ocean observing system to have a stronger impact on the NWS boundaries.

To assess the interannual variability in the boundary conditions we calculate time-series of ocean boundary conditions for the CO6 domain from PDCtrl and PDCtrlOcean, and call them PDCtrlBCs and PDCtrlOceanBCs respectively. We use modelled SST and SSS instead of upper 30m depth-averaged T and S, and use annual means rather than the daily means used in the AtlantOS_BB_BC and AtlantOS_WBC_BC. An example is shown in Figure 2.4 for the 80-year period of the PDCtrl run. As PDCtrlOcean has climatological ocean boundary conditions, there is no interannual variability in the PDCtrlOcean timeseries. Therefore the difference between the PDCtrlBCs and PDCtrlOceanBCs timeseries is simply the interannual variability in the PDCtrl. The interannual standard deviation of the SST boundary timeseries in PDCtrlBCs, ranges from 0.29°C – 1.15°C across the different boundary regions of Table 2.1, with a mean of 0.46°C, while for SSS the PDCtrlBCs standard deviations range from 0.04 to 0.32, with a mean of 0.11. These values are much greater than the biases and rms values between the AtlantOS_BB_BC and AtlantOS_WBC_BC, which represent high frequency variatiability.

The 2-year OSSE studies conducted under AtlantOS Task 1.3 give valuable information on the impact of additional observations on high frequency (daily to seasonal) variability in the CO6 lateral ocean boundary conditions. We have shown that this influence is small. However longer OSSE experiments would be required to determine whether additional observations would constrain the CO6 bounadries on interannual timescales. Our conclusions might also be biased by the fact that the BB observing system run already does a good job of constraining the temperature and salinity in the Northeast Atlantic to be close to the Nature Run (see Figure

A.5 of AtlantOS Deliverable 1.5). It is possible that the free model version of FOAM is already quite close to the Nature Run in this region, despite these two models differing in a number of aspects of resolution and parameter settings. One might expect the FOAM model to be more biased relative to the real world than it is relative to the Nature Run, in which case the data assimilation would have a larger impact.

SST SSS

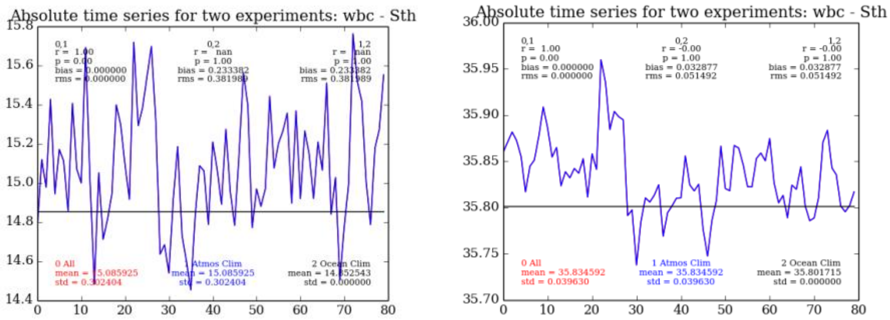


**Figure 2.4 Example time series of SST (left) and SSS (right) boundary conditions for the southern portion of the Western boundary (south of 52.5°), from PDCtrl (red), PDCtrlAtmos (blue) and PDCtrlOcean (black). Note that modelled boundary T and S follow the ocean boundary conditions, and so PDCtrl and PDCtrlAtmos are identical, having the same boundary conditions. Note PDCtrlOcean (black) has no interannual variability).**

## 2.3 Conclusions

We have shown that there is a correlative relationship between the NWS temperature and salinity and the oceanic boundary conditions (Section 1). To test whether this correlation reflects a mechanistic link, we have run a series of sensitivity experiments to see how much of the shelf variability is linked to the oceanic (and atmospheric) boundary conditions. The results suggest that the salinity relationship is causative, although relatively weak, and of limited geographic extent. The NWS temperature interannual temperature variance appears to be almost exclusively atmosphere-driven, with both the NWS temperatures and the ocean boundary conditions linked to atmospheric forcing.

By analysing the OSSE experiments of AtlantOS Task 1.3 we have estimated the impact of additional open ocean observations on the open ocean boundaries of the CO6 regional model. On short timescales (daily to seasonal) the influence of additional Argo sampling in the western boundary currents and equatorial regions is small at the CO6 boundaries, despite giving an overall improvement in RMS errors over the Atlantic basin as awhole (Deliverable 1.5).

While this appears a somewhat negative result, several caveats should be borne in mind:

1. One would expect the influence of open ocean observations on the CO6 boundaries to be more evident on longer (interannual to decadal) timescales. This cannot be assessed with the 2-year OSSEs available, and a longer OSSE study (reanalysis timescale) is required.
2. Assimilating an improved global ocean observing system would be expected to have an impact on atmospheric circulation (e.g. through the influence of North Atlantic SSTs on the storm track). Since we have shown that much of the NWS variability comes from the atmospheric forcing, this seems a likely pathway for influence of the ocean observing system on the NWS. Coupled data assimilation experiments would be needed to demonstrate this, which would be beyond the scope of the present study.
3. Although the Nature Run model has several differences from the FOAM model used in the OSSE experiments, the bias between the FOAM and Nature Run models is likely to be less than the bias between either model and the real world. Hence the impact of data assimilation (and of the additional observations) is likely to be under-estimated by

the OSSE experiments. This could be addressed by further OSSE experiments in which one of the models was deliberately degraded to increase the bias.

4. The remote influence of the additional western boundary observations on the whole basin is not explicitly captured by current data assimilation schemes, which use relatively short covariance scales. Recent developments (Thomas and Haines 2017) suggest that it may be possible to assimilate boundary data in a way that has a basin-wide spatial influence.

These caveats point to further research which would be needed to establish fully the potential of additional ocean observations to improve modelling of the NWS.

## 3. Published and planned publications from this work

Tinker, J., Krijnen, J., Wood, R., Barciela, R. and Dye, S. (2018). "What are the prospects for seasonal prediction of the marine environment of the NW European shelf?" Ocean Science **14**: 887-909 https://doi.org/10.5194/os-14-887-2018.

Tinker, J., Palmer, M. D., Howard , T. P., Lowe, J. and Copsey, D. (in preparation). "Quantifying Coastal Sea Level Variability around the UK."

## 4. References

Roberts, C. D., Calvert, D., Dunstone, N., Hermanson, L., Palmer, M. D. and Smith, D. (2016). "On the Drivers and Predictability of Seasonal-to-Interannual Variations in Regional Sea Level." Journal of Climate **29**: 7565-7585 http://dx.doi.org/10.1175/JCLI-D-15-0886.1.

Tinker, J., Krijnen, J., Wood, R., Barciela, R. and Dye, S. (2018). "What are the prospects for seasonal prediction of the marine environment of the NW European shelf?" Ocean Science **14**: 887-909 https://doi.org/10.5194/os-14-887-2018.

Tinker, J., Palmer, M. D., Howard , T. P., Lowe, J. and Copsey, D. (in preparation). "Quantifying Coastal Sea Level Variability around the UK."

Thomas, C. M. and K. Haines, 2017: Using lagged covariances in data assimilation. TELLUS SERIES A-DYNAMIC METEOROLOGY AND OCEANOGRAPHY, **69**,Article Number: 1377589

Wakelin, S. L., Holt, J. T. and Proctor, R. (2009). "The influence of initial conditions and open boundary conditions on shelf circulation in a 3D ocean-shelf model of the North East Atlantic." Ocean Dynamics **59**(1): 67-81 10.1007/s10236-008-0164-3.

Williams,K.D., D. Copsey, E.W. Blockley, A. Bodas-Salcedo, D. Calvert, R. Comer, P. Davis, T. Graham, H.T. Hewitt, R. Hill, P. Hyder, S. Ineson, T.C. Johns, A. Keen, R.W. Lee, A. Megann, S.F. Milton, J.G.L. Rae, M.J. Roberts, A.A. Scaife, R. Schiemann, D. Storkey, L. Thorpe, I.G. Watterson, D.N. Walters, A. West, R. Wood, T. Woollings and P.K. Xavier, 2017: The Met Office Global Coupled model 3.0 and 3.1 (GC3 & GC3.1) configurations. *J. Adv. Model. Earth Sys.*, http://onlinelibrary.wiley.com/doi/10.1002/2017MS001115/full , doi:10.1002/2017MS001115.