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Optimising and Enhancing the Integrated Atlantic Ocean Observing Systems

Towards an improved design of the in-situ observing system for ocean reanalysis, analysis and forecasting: design of experiments

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1. Introduction

1.1. General presentation

This document contains the report on the design of Observing System Simulations Experiments (OSSEs). It corresponds to the work carried out as part of Task 1.3 of AtlantOS WP1.

It is the deliverable D1.2 identified in the description of action, which is due by the end of March 2016 (T0+12), T0 being the 1st of April 2015.

The AtlantOS project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement n° 633211.

1.2. Observing System Design Experiments

Task 1.3 is divided in 5 subtasks:

- Subtask 1: Toward an improved design of the in-situ observing system for ocean reanalysis, analysis and forecasting: physical variables (Mercator Ocean, Met Office, CLS, ECMWF, CMCC)
- Subtask 2: Toward an improved design of the in-situ observing system for ocean reanalysis, analysis and forecasting: biogeochemistry and carbon variables (CNRS, Met Office, Mercator Ocean)
- Subtask 3: Use of statistical techniques for identifying an optimal observational network for enabling ocean carbon system estimates (CNRS/LSCE, University of Exeter)
- Subtask 4: Design of the Integrated Atlantic Ocean Observing System to support climate prediction and detection of change (Met Office, NOC)
- Subtask 5: Coordination (Ifremer)

This report gathers all the work planned by the different groups within all subtasks of Task 1.3 to assess possible extensions of the Atlantic in situ observing network. The assesment will be performed using different approaches to increase the robustness of the conclusions.

1.3. Acronyms

CMEMS: Copernicus Marine Environment Monitoring Service

NAO: North Atlantic Oscillation

MOC: Meridional Overturning Circulation

OGCM: Ocean General Circulation Model

OSE: Observing System Evaluation

OSSE: Observing System Simulation Experiment

SLA: Sea Level Anomaly

SST: Sea Surface Temperature

WBC: Western Boundary Current

2. Design experiments

2.1. Design experiments for the physical variables (Mercator Ocean, Met Office, CLS, ECMWF, CMCC)

Design oriented studies for physical description of the ocean will be conducted to improve the efficiency of the in situ Atlantic network to constrain ocean state estimates. Various approaches will be used to get different insight on the tested extensions. The impact of the chosen scenarios will be assessed in the context of Copernicus Marine Service operational analysis and forecasting systems. The scenarios to be tested are discussed within AtlantOS with the groups responsible of the instrument deployment.

The in situ network is not considered as a stand alone contribution but as a component of an integrated ocean observing system including remote sensed observations.

Four groups will prepare, run and analyze OSSEs covering 1 to 2 years (MetOffice, Mercator Ocean and CLS and CMCC). ECMWF will carry out OSEs (Observation System Evaluations) with its reanalysis system and identify important ocean regions using reanalyses with multiply ensemble members. The observation requirements from the different systems will be given at the end of the project. The use of different systems and approaches should help to discriminate the efficiency of the different scenario tested and lead to more robust recommendations.

2.1.1. *Nature run model simulation and qualification*

The OSSEs will cover up to two years from summer 2008 to summer 2010. Those two winters have opposite NAO signals and were chosen for the biogeochemical OSSEs.

A nature run at high resolution (1/12°) will serve as the “true” ocean to simulate the observations that will be used to get ocean state estimations. The nature run was produced with the new Copernicus global high resolution system called PSY4 and operated at Mercator Ocean, but without data assimilation. It is based on the NEMO OGCM code with an ORCA grid at 1/12° resolution. It is forced by the ECMWF atmospheric analysis from 2006 to 2014. Daily outputs and observation misfit diagnostics are produced and stored at Meteo France supercomputer. Qualification of the nature run in term of representativeness of the ocean variability will be done.

In order to be able to share the files between the different groups within Task 1.3 and other groups within AtlantOS, the nature run 3D fields at high resolution will be interpolated onto a coarser grid at ¼° resolution. This is also required to compare the nature run with the different system analysis outputs.

2.1.2. *Simulation of the observations*

Both remote sensed and in situ observations will be simulated from the nature run. The observation positions representative of recent years will be chosen. Then additional observations corresponding to potential extensions will be simulated with a precise error specification. The later one will influence the importance of the additional network and its capacity to detect a given phenomenom depending on the ratio between the error and the variance of the signal.
The observation files will at least include the position in time and space of the observation, the value of the model at this location.

The observation networks that will be simulated are, at least:

- In situ temperature and salinity profiles (Coriolis/CMEMS data base extraction for positions),
- Jason-2, Sentinel S3a and b along track SLA,
- Daily SST maps,
- Sea ice concentration maps.

In their default setup, not all the systems are assimilating the same observations but all of them will be extracted from the same nature run.
A specific treatment will be applied to the Argo profile simulation to ensure a more homgeoneous sampling of the ocean than the real one, using a combination of positions of different years. Then the sampling will be increased by a factor of 2 in WBC and tropical regions as suggested by JCOMMOPS.

Few scenarios among the proposed extensions will be tested depending on their potential interest for improving ocean basin scale monitoring in real time and ocean reanalysis.

2.1.3. *Preparation of the analysis tools*

Before running the "design" experiments with the different approaches, each of the system used will need to be updated and tuned to assimilate efficiently the observation from the future network extension.
In the data assimilative systems and ARMOR 3D, observation operators will be defined or improved for the new observations and new observation file handling routines will be coded. ARMOR 3D is a multivariate ocean state reconstruction tool with observations only.

ECMWF will develop a new high-resolution (1/4° degree) Ocean ReAnalysis System 5 (ORAS5) with ensemble generation.

CMCC will generate a Reference ensemble of simulations to estimate a statistical forecast error covariance matrix and evaluate how the different observation arrays can observe it. This approach does not depend on the full assimilation scheme parameters but gives the potential efficiency of a given network to reduce the forecast error. The ensemble production will require the definition of perturbations that produce a realistic ensemble spread.

2.1.4. *OSEs*

Some matching calibration OSEs with real in situ observations similar to the one tested in the OSSEs will be done to verify that the OSSE conditions are realistic in terms of innovations and residuals. It will also give very usefull insight on the data assimilation system capacity to use those observations before testing any extension of existing networks.

ECMWF will carry out OSEs using ocean reanalysis system to identify important ocean regions and observations. A selection of impact indicators with high forecasting skills and their relation to ocean variables (i.e. T20 thermocline depth) will be studied using reanalyses with multiply ensemble members. The relation of the Atlantic Tropical Cyclones indicator to subsurface ocean variables using ORAS5 and ORAS5-LW (1 degree) with model ensembles spread will also be explored statistically.

Two options will be tested for the OSEs:

- Option 1: Specific OSEs by remove observing system components in a given area
    a. Removal of altimetry observation of Sea Levels in different ocean regions (i.e. Atlantic Ocean)
    b. Removal of ocean in-situ observation of mooring profiles (T/S) in the Tropics (i.e. Atlantic Ocean and/or Pacific Ocean)
    c. Carry out single observation experiment using simulated observations
- Option 2: Blanket OSEs by removing observing system components everywhere, i.e. removal of Argo float observation.

2.1.5. *"Design" experiments*

It was agreed during the September 2016 meeting, that some OSSE will be done and analysed in common within the different groups, others will be chosen depending on the main focus and applications of each group.
Here are the common OSSE experiments that will be carried out with the MetOffice, CLS, CMCC and Mercator Ocean systems:

- "Backbone" experiment: assimilation of SST, along track SLA, Argo, moorings and XBT,
- Addition of Argo profiles in WBC and tropics to the backbone setup.

The following OSSEs will be done by at least three groups:

- Impact of deep Argo profiles (4000 and/or 6000 m depth),
- Impact of gliders and their possible extensions.

The impact of drifters with an additional thermistor chain from the surface to 150 meter depth will be tested with at least one system.

Internal assimilation parameters such as representativity error, observation rejection criteria may be shared depending on the different system specificities. Instrumental error will be the same for all systems and defined in agreement with the networks.
The extension scenario will be tested toward their efficiency to reduce the forecast and analysis error in the different data assimilation systems and observation based inversion system (ARMOR3D).

2.1.6. *Analysis of the experiments (MetOffice, Mercator Ocean, CLS, CMCC)*

Common metrics will be used: assimilation diagnostics to measure the error reduction on observed and unobserved model variables and physical/process oriented diagnostics depending on the goal of the different observation network. Synthesis of the design experiments into guidance for observing networks will then be done.

2.2. Design experiments for the biogeochemical variables (Met Office, Mercator-Ocean and CNRS experiments)

2.2.1. *Objectives and common approach*

The objective of the sub-task is to deliver guidelines to improve existing elements and implement new components of the Atlantic Observing System dedicated to ocean reanalysis, analysis and forecasting of biogeochemical variables. In this sub-task, the focus is set on nutrients, oxygen, Chl-a and pH observations. The objective of the workshop was the outline of a common approach based on numerical models that will be used by the three groups (CNRS, Met Office, Mercator Ocean) in charge of the sub-task.

It was decided at the AtlantOS OSSEs meeting in December 2015 that the three groups involved will each test the same observing scenarios, but using separate systems and experiments, so there will be no shared nature run. Free-running physics would be used in all cases, with no physical data assimilation. The experiments will be run for a year-long common assessment period from 1 March 2009 to 28 February 2010, which covers a period of large NAO and MOC variability. The period also matches the first year of the period to be used for the physical OSSEs. It was also decided that ensemble-based experiments will be considered as a backup solution in case of issues with conventional OSSEs.

2.2.2. *Observing scenarios*

Observing scenarios will focus on testing different distributions of BioArgo, as well as the value of satellite ocean colour data.

Initially, the following scenarios will be assessed:

- #0: No data assimilated (nature run)
- #1: Ocean colour data (reference scenario)
- #2: Ocean colour data and BioArgo sensors on ¼ of existing Argo array
- #3: Ocean colour data and BioArgo sensors on full existing Argo array

All observations to be assimilated will be sampled from the nature run. Ocean colour tracks will be taken from the L3 daily 4km CMEMS global product for the simulated period, and treated by each group as they normally would, with a nominal assumed instrument error of 30%. The simulated period is covered by the MODIS, MERIS and SeaWiFS sensors, so coverage is broadly comparable to that expected in the near future from MODIS, VIIRS and OLCI. BioArgo floats will be considered to have chlorophyll, nitrate, oxygen and pH sensors. The existing Argo array distribution will be the same as used for the physical OSSEs, and the ¼ scenario will be sub-sampled from this. Nominal values for instrument error will be provided by the observing networks, with the total observation errors used (i.e. including representativity error) to be decided by the individual groups.

A further scenario, to assess existing OceanSITES moorings and glider data, will be defined and run once initial results have been obtained for the above scenarios. In addition, scenarios with a majority of Bio-Argo and fixed moorings (some of them equipped with additional acoustic sounders to sample zooplankton and fish biomass) concentrated in the sub-polar gyre will be considered as part of WP5.3 (regional observing systems), as well as experiments to assess the sampling frequency of BioArgo floats.

2.2.3. *Model experiments*

The proposed model runs will all use NEMO in the ORCA025 configuration and no physics DA. They will include:

- Standard model runs,
- Runs with perturbed biogeochemical model parameters, surface perturbation forcings and internal stochastic forcings.

Met Office. The Met Office currently has the capability to assimilate ocean colour and pCO_2 data, and is developing the capability to assimilate profiles of chlorophyll, nitrate, oxygen and pH, based on the NEMOVAR assimilation framework. The Met Office is currently transitioning its global biogeochemical model from HadOCC to MEDUSA – it is planned to use MEDUSA for these experiments, but HadOCC will be available as a back-up if the transition is not complete.

All Met Office model runs will:

- Use a coupled physical biogeochemical model, either FOAM-MEDUSA or FOAM-HadOCC
- Use a global ORCA025 configuration
- Cover the common assessment period from 1 March 2009 to 28 February 2010
- Start from spun-up initial conditions taken from a previous experiment
- Assimilate simulated ocean colour data, using the 3D-Var NEMOVAR scheme (Waters et al., 2015) combined with a multivariate nitrogen balancing scheme (Hemmings et al., 2008; Ford et al., 2012)
- Assimilate simulated profiles of chlorophyll, nitrate, oxygen and pH using the 3D-Var NEMOVAR scheme
- Not assimilate any physical observations
- Be forced by ERA-Interim atmospheric fluxes

The following model runs are proposed:

- Nature run
- Run with perturbed biogeochemical model parameters
- OSSE runs for different observing scenarios

The nature run will be a run of the standard model configuration as described above. The run with perturbed biogeochemical model parameters will differ from the nature run in the settings of key biogeochemical model parameters. Physical fields may also be perturbed, based on the results of preliminary experiments. Pseudo-observations of chlorophyll, nitrate, oxygen and pH will be created from the nature run, consistent with the scenarios to be tested in the OSSEs, with the OSSE runs assimilating these into the perturbed run. The type of assessment to be performed is detailed below.

Mercator-Océan. Mercator-Océan is currently developing the assimilation of biogeochemistry observations (both from satellite and *in situ* profilers) in the global PISCES model. Nevertheless, the data assimilative system is not sufficiently mature to perform OSSEs with *in situ* observation. Thus, Mercator Ocean tasks will focus on the implementation of statistical methods for the analysis of the objective performances, as well as the optimal design, of the BioArgo array. An ensemble-based method - the so-called ArM methodology (*cf.* Le Hénaff *et al.*, 2009; Lamouroux *et al.*, 2016) – will be applied. It relies on a statistical comparison of the model (here PISCES) uncertainties and the observation errors, and allows both a qualitative and quantitative evaluation of the performance of the observation network at detecting the prior (model) uncertainties (based on hypotheses on error sources). The PISCES ensemble (in a global configuration) will be produced – in a first approximation - as a response to perturbations of the physical forcing. The ArM method will be applied to a specific season (for instance spring, in order to have a dedicated focus on the representation of the bloom in the North Atlantic) with the observing scenarios detailed above. The physical ensemble of NEMO global simulations will be produced in 2016 and will thus be used to constrain an offline version of PISCES. First objective is to obtain a satisfactory ensemble spread for the main biogeochemistry variables in the mixed layer. In 2017, the ArM method will be applied to some BioArgo array configurations of interest (see above) to answer several questions, among which: Which model regions – and associated uncertainties - are most variable in space and time, for the observed variables, and therefore need the highest (or optimal) sampling frequencies? How are *in situ* observations likely to complement the data currently obtained from satellite ocean colour?

CNRS/LGGE. CNRS is developing the assimilation of biogeochemistry observations (both from satellite and *in situ* profilers) in a North Atlantic NEMO-PISCES configuration. The assimilation system is currently tested for satellite ocean colour data and it will be extended to include assimilation of chlorophyll, nutrient (and possibly oxygen) vertical profiles in 2016. It is expected that the assimilation system will be ready for OSSEs experiments in 2017. The assimilation approach will include a combination of stochastic ensemble runs and reduced-rank analysis with anamorphic transformation (Brankart *et al*., 2012 ; Fontana *et al*., 2013). The stochastic perturbations are introduced into the model formulations to simulate 2 classes of uncertainties: the uncertainties on biogeochemical parameters and the uncertainties induced by unresolved scales in the presence of non-linear processes. Using these stochastic parameterizations, a probabilistic version of PISCES is designed and 60-member ensemble simulations will be performed in a first stage to diagnose the space-time variability, assess the regions of dominant variability and identify hot spots of biogeochemical activity. OSSEs will be performed in a second stage using the observing scenarios agreed by the participants, focusing on analyzing the complementarity between satellite ocean colour (from LEO missions, e.g.Sentinel-3, or new GEO mission concepts in development) and in situ Bio-Argo floats.

2.2.4. *Science questions and metrics*

Main science questions will include:

- Which regions are most variable in space and time, for the observed variables, and therefore need the highest sampling frequencies?
- What impact are these observations likely to have on key end-user requirements such as primary production (for input to ecosystem models) and air-sea CO_2 fluxes (complementing WP1.3.3 on ocean carbon)?
- In which regions and times of year is knowledge most required on vertical structure of chlorophyll and nitrate?
- How are in situ observations likely to complement the data currently obtained from satellite ocean colour?

The main variables to be assessed are the assimilated variables (chlorophyll, oxygen, nitrate, pH), plus primary production and air-sea CO_2 fluxes. Other model variables will be assessed as appropriate, and an important focus will be the position of deep chlorophyll maxima and the nutricline. Some common metrics will be defined once initial results have been obtained, including the use of a common area mask based on Longhurst provinces (Longhurst et al., 1995).

2.3. Use of statistical techniques for identifying an optimal observational network for enabling ocean carbon system estimates (CNRS/LSCE, University of Exeter)

Delay to a delay in hiring the post-doctoral researcher involved in subtask 2.3, activities outlined below start in January 2017 and will run over 24 months.

2.3.1. *Objectives*

The objective of this sub-task is to provide guidelines for the development of the integrated observing system of carbon variables, which will enable the release of carbon system estimates at the scale of the Atlantic basin at monthly, respectively seasonal frequencies. Observing system experiments rely on the combination of a long coupled ocean biogeochemical general circulation simulation (e.g. NEMO/PISCES, ¼° horizontal resolution, forced by an atmospheric reanalysis over the years 1958 to 2012, including anthropogenic CO2) covering the Atlantic Ocean with a statistical model. A probabilistic approach will be developed in order to address various sources of uncertainty (e.g. analytical error, mismatch of spatial and temporal scales between different observing systems, interpolation error of gridded products) and their spreading to the final product.

2.3.2. *Scientific questions*

Observing system experiments will allow addressing the following three key questions:

Q1: What is the impact of an improved set of physical/biogeochemical drivers for the construction of surface ocean pCO2 distribution?

(1) Make use of float and glider trajectories provided by physical design experiments presented under 2.1 to extract driver variables from coupled physical-biogeochemical simulation;

(2) Evaluate additional driver data either from remote sensing (SSH, SST, wind) or *in situ* depth-resolved observations (e.g. alkalinity (ALK), dissolved inorganic carbon (DIC), pCO2, pH, nutrients), as well as derived products such as heat flux at the air-sea interface;

Q2: impact of improved observing system for biogeochemical drivers (pH, Chla) and pCO2, ocean ?

Build on observing system simulation experiments developed under 2.2 to assess impact of BioArgo sensors for Chla, pH and pCO2 for constructing basin-wide pCO2 maps

Q3: What are major sources of uncertainty?

(1) data: assess the contribution of uncertainties coming from driver data: (i) analytical error, (ii) measurement and model error for remote sensing data, (iii) interpolation error (gridded products), (iV) mismatch of spatial/temporal scale between products from different observing plateforms;

(2) model: (i) systematic model biases in ocean physics and simulated biogeochemistry; (ii) spatial resolution.

2.3.3. *Observing scenarios*

(1) Evaluation of existing network:

Observing scenarios will focus on the combination of existing space and in situ observing plateforms (VOS lines, repeated hydrographic sections, moorings) with the goal of

(a) the assessment of the existing carbon observing system

(b) the identification of key undersampled areas as priority areas for future sensor deployments.

The performance of the statistical model to construct surface ocean pCO2 distributions from a combination of sparse driver data will be evaluated against observations from the Surface Ocean CO_2 Atlas (SOCAT) and results from models used by the community (Rödenbeck et al.).

(2) design studies:

Observing scenarios will focus on testing different combination of novel drivers data. Scenarios will follow the scheme outlined under 2.2.2 for BioArgo. The reference state is provided by surface ocean pCO_2 distributions from a NEMO/PISCES simulation without data assimilation. The combination of pH from Argo floats and alkalinity derived from an empirical relationship with salinity will be tested and compared to a scenario of future deployment of pCO2 sensors on floats.

The following suite of design experiments is planned:

(a) NEMO/PISCES ¼° reference scenario

(b) pCO2 maps produced from existing network, base line

(c) existing carbon observing network and BioArgo sesnors for pH or pCO2 on ¼ of existing Argo array

(d) existing carbon observing network and BioArgo sensors pH or pCO2on full existing Argo array

2.3.4. *Coordination within WP1 and across WPs*

Design studies are coordinated with other WP1 partners. Input for potential evolution of existing networks are taken from WP2 and WP3 partners.

Results from the statistical approach will be compared with those from Subtask 2. It is expected that insights from Subtask 3 will lead to improved approaches to data assimilation, and such improvements will be tested in Subtask 2 if they emerge early enough in the project.

2.4. Design of the Integrated Atlantic Ocean Observing System to support climate prediction and detection of change (Met Office, NOC)

AtlantOS Task 1.3.4: Design of the Integrated Atlantic Ocean Observing System to support climate prediction and detection of change. Coupled climate model simulations (as our best estimate of future change) will be used to quantify the observing network required to detect emergent climate change signals, with focus on the deep ocean and potential hot spots needing targeted sampling.

2.4.1. *Background*

For the purposes of climate monitoring and attribution, an ideal Integrated Atlantic Ocean Observing System will be capable of quantifying signals associated with climate change and variability with sufficient accuracy to calculate budgets of key climate variables (e.g. heat, freshwater). However, the characteristics of future change may be different from the changes in the historical past (for example as more heat and anthropogenic carbon enter the deep ocean). This subtask will inform the development of a ’future-proofed’ Integrated Atlantic Ocean Observing System by using coupled climate model simulations (as our closest estimate of future change) to quantify the observational network required to constrain both internal variability as well as the emergent signals of climate change.

2.4.2. *Scientific goals*

The focus of the work will be around determining the space and time scales and the accuracy with which candidate observing systems can determine the large scale heat and fresh water budgets of the Atlantic Ocean. Uptake of heat by the ocean is a fundamental metric of the Earth’s energy imbalance and so crucial to understanding events such as the recent hiatus in global surface warming. Changes in the distribution of fresh water are potentially a powerful way to detect the changing water cycle in response to climate change, as well as affecting the large scale ocean circulation, for example the stability of the MOC. The ability to accurately determine budgets is fundamental to developing an understanding of ongoing climate change, but the present observing system has limited ability to constrain budget terms such as total ocean heat content and section heat transports, and these deficiencies may become greater with increased heat uptake by the deep ocean under future climate change. Specifically, recent climate model studies by the Subtask 4 team and collaborators have shown that estimating global ocean heat content based on sampling the ocean above 2000m only (the current depth of the Argo array) would have been good enough to constrain the planetary energy budget to within ± 0.1 Wm^{-2} for the past century, but for the 21st Century would lead to errors of order 0.2 Wm^{-2}. Deeper observations, particularly in the Atlantic and Southern Oceans, will be required to constrain the 21st Century energy budget, and hence to quantify the rate of climate change as it evolves (C. Roberts/F. Garry, pers. comm.).

The goals of this activity are two-fold:

- Theme 1: Determine the uncertainties inherent in basin-scale heat budget estimates that are based on the historical observational record, how these uncertainties can be minimised by appropriate choices of infilling algorithm
- Theme 2: Determine priorities for future observing system design (e.g. deep Argo, section heat transport sampling), to constrain basin scale heat content in a changing climate (informed by results of Theme1)

The primary focus will be on heat and on decadal timescales. Fresh water content will be considered if time and resources allow.

2.4.3. *Plans*

Initial work is already under way and is contributing to Theme 2. This focuses on the completion and publication of preliminary results on future heat penetration into the global ocean and the consequent requirements for deep (>2000m) sampling. A range of CMIP5 models is being analysed, on the assumption that the ocean is perfectly sampled down to a particular depth horizon. Errors in heat content estimates are evaluated for various scenarios (specifically: no sampling below 700m; no sampling below 2000m; sample globe to 2000m plus Southern Ocean to 4000m; sample globe to 2000m plus Southern Ocean and Atlantic to 4000m; sample globe to 4000m). In this initial phase the sampling period for heat content estimation is 10 years, and the model integrations considered are: pre-industrial control (PIC); historical forcing (1850-2005); RCP 8.4 (2005-2050); RCP8.5 (2050-2100). Following completion of this work (currently estimated by end 2016), the implications for future observing systems will be discussed with the Deep Argo and glider communities. Followup work is identified under Theme 2 below. This work is being performed in collaboration with Southampton University.

Theme 1: *Determine the uncertainties inherent in basin-scale heat content estimates that are based on the historical observational record, how these uncertainties can be minimised by appropriate choices of infilling algorithm*

This work will use one or more eddy-permitting climate model(s) to generate “synthetic” ocean profile data sets of temperature and salinity for a variety of different climate change scenarios (e.g. historical, future projections). Specifically, a historical ocean simulation (1958-2015) using the UK’s NEMO-ORCA12 (1/12 degree resolution) configuration will be the initial source.

Synthetic profiles will be mapped using the same algorithm as is used for the EN4 statistical analysis and compared to the model truth to evaluate the uncertainties associated with mapping technique.

In a parallel strand of work, the variability of heat transport across key ocean sections will be assessed, in order to determine how frequently these transports need to be sampled in order to constrain large scale regional heat budgets to within a given tolerance. A large (~100 member) historical ensemble of the MPI-ESM1model will be used to improve understanding of signal to noise and detection issues.

The results will be synthesized to assess our capability to assess historical ocean heat budgets on at least global and ocean basin scales. If time and resources permit an early assessment will be made of fresh water budget estimates.

The approach will be extended to smaller scale features. The pseudo-profiles will be used to assess various mapping approaches (e.g. interpolation on neutral density or depth surfaces; gaussian vs non-gaussian and multi-scale approaches to determining decorrelation length scales), by comparing interpolated pseudo-profiles with model 'truth'. This work has the potential to feed into development of data assimilation techniques.

The synthetic profiles will be made available to the wider scientific community to facilitate extension to different mapping methodologies, or observing system designs (subsampling) depending on the participation of additional project partners/external collaborators. Generic software will be made available to allow collaborating groups to sample a wider range of model runs/scenarios.

Outputs from this work (expected around late 2017) will be:

(i) A flexible python tool for extracting synthetic versions of the EN4 profile database from arbitrary ocean/climate model data.

(ii) Synthetic profile data sets (and the associated model 'truth') from at least the historical ORCA12 run described above for the evaluation of mapping methodologies. The profiles will also be derived from the hiResMIP run described above if time and resources permit.

(iii) An assessment of sampling uncertainties and bias for basin scale heat budgets and for specific regional features, associated with different candidate approaches to infilling the historical observation database.

Theme 2: *Determine priorities for future observing system design (e.g. deep Argo), to constrain basin scale heat content in a changing climate*

The first task is completion of the assessment of heat content with idealised 'perfect observation above various depth horizons (work already under way, as described above). This may later be extended to cover heat content estimates for periods both longer and shorter than 10 years.

A second strand of work will extend the pseudo-profile approach to simulated future climate change using high resolution coupled models, to determine whether sampling and infilling algorithms need to change to detect future climate changes. The number of models to be examined is still under discussion, but it is expected to include the same ORCA12 ocean model described above, coupled to a high resolution (25km) version of the Met Office UM atmosphere model and run for the period 1950-2050 as part of the HiResMIP project (part-funded by Horizon2020 PRIMAVERA). Additional runs particularly looking beyond 2050, are likely to be with moderate resolution (~0.25 degree ocean) coupled models, which are expected to be typical for CMIP6. Standard CMIP6 DECK experiments are expected to be completed with such a model by the Met Office by Spring 2017.

The study of section heat transport variability will be extended to future changes using a ~70 member ensemble of MPI-ESM1.

As for Theme 1, results will be synthesized to assess our capability to constrain future changes in basin-scale ocean heat budgets analyses, based on current and potential future observing systems. Analysis will be extended to fresh water content towards the end of the project if resources allow.

Outputs:

(i) an assessment of the deep Atlantic ocean patterns of climate change and variability in CMIP5 models

(ii) estimates of when/where existing observing technologies become inadequate for constraining basin scale heat budget changes in the Atlantic.

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