AtlantOS

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Comments	The deliverable is the final deliverable of Task 1.3. This is a short synthesis of Task 1.3 results that focuses on recommendations for the IAOOS. D1.6 builds on deliverable D1.5 (synthesis of OSSEs). Deliverable was delayed to take into account the latest version of D1.5 and a recent update of Task 1.3 scientific publications.

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Stakeholder engagement relating to this task*

WHO are your most important stakeholders?	☐ National governmental body ☐ International organization Please give the name(s) of the stakeholder(s): World Climate Research Programme Global Ocean Observing System Copernicus Marine Service Euro-Argo ERIC, EuroGOOS, EOOS
WHERE is/are the company(ies) or organization(s) from?	Please name the country(ies): International
Is this deliverable a success story? If yes, why? **If not, why?**	☐ Yes, based on a comprehensive assessment of the impact of different observing elements in modelling and data assimilation systems, more precise and evidenced based recommendations for the development of an integrated Atlantic observing system are given.
Will this deliverable be used? **If yes, who will use it?** **If not, why will it not be used?**	☐ Yes, the results (and publications in the peer reviewed literature) will be used to by WP1 to elaborate long term plans to the evolution of the Atlantic observing system.

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.

Task 1.3 synthesis and recommendations

The goal of task 1.3 was to deliver objective guidelines to improve existing elements and/or implement new components of the Atlantic observing system. The general approach was based on OSSEs (Observing System Simulation Experiments). OSSEs rely on physical and coupled physical-biogeochemical models that realistically represent the space-time variability of the EOVs to be monitored, with data assimilation to optimally merge in-situ and satellite observations with models. OSSEs were mainly based on the modelling and assimilation capacity developed by the European research community in connection with the Copernicus Marine Service. Approaches using statistical methods for optimal array design have been used to provide complementary insights. Climate model outputs were also analysed to test the potential of Atlantic observing system to detect expected changes in future decades.

OSSEs are based on integrated global and regional ocean observing systems. They take into account the role of modelling and data assimilation (i.e. a model forecast provides a better a priori information compared to climatology) and the impact of a given observing system is not analysed independently of the other components (e.g. impact of Argo takes into account the synergy with satellite altimetry). This provides a much better and more realistic measure of the impact of a given observing system.

Task 1.3 was carried out over a 3.5 year time period (April 2015 – December 2018). Four workshops (December 17&18, 2015; September 7&8, 2016, May 3&4, 2017 and November 24, 2017) were organized to discuss the design of OSSEs, first, intermediate and final results. Workshops involved Atlantos WP2&WP3 network experts together with Task 1.3 experts.

A comprehensive description of all Task 1.3 results is given in Atlantos D1.5 ("Synthesis of OSSEs results"). Task 1.3 also led to a large number of peer reviewed scientific publications with 4 publications already published, 4 submitted and 7 in preparation (see list below).

We provide here a short synthesis of task 1.3 achievements:

- For the first time, a coordinated multi-model OSSE has been carried out to assess the potential of a range of observing elements to better estimate the physical state of the Atlantic Ocean. This represents a major advance in the robust evaluation of observing systems. Common protocols (e.g. sharing the same nature run, common diagnostics) were used and this contributed to the development of best practices and standards for observing system design.
- Work carried out in Task 1.3 evidenced the complementary nature of satellite and in-situ observing systems to constrain modelling and data assimilation systems for physics. The present backbone system (multiple altimeters, satellite SST observations from microwave and infrared sensors, Argo, moorings, XBT) can be effectively assimilated in ocean models and allow constraining efficiently upper ocean fields.
- There is now a much better understanding of the impact of physical (temperature and salinity) Argo enhancement (deep Argo, enhancing the resolution in western boundary and tropical regions) on modelling and data assimilation systems, and this needs to be continuously reinforced by demonstrating its added value at specific space/time scales and based on process-oriented metrics.

- Compared with a baseline physical Argo network which is uniformly distributed across the ocean, increased Argo density in western boundary currents and along the equator results in improved estimates of temperature and salinity for the entire Atlantic. The improvements are particularly noticeable in the 300-2000m depth range, with a higher impact on salinity than temperature fields at short time scales.
- OSSE results demonstrated the major impact of a deep Argo array to constrain modelling data assimilation systems at depths below 2000 m. A deep Argo array, with 5°x5°spacing and monthly sampling to either 4000m or the bottom, would lead to substantial improvement in deep temperature and salinity estimates (20 to 40% error reduction). Sampling below the current 2000m depth through deep Argo floats will also be important to track ocean heat content and climate change as warming progresses in the 21st Century. This deeper penetration of heat begins to become significant around the year 2000 in the models studied, and is particularly strong in the Atlantic and Southern Oceans, indicating where we may expect to get the greatest added value from early deployment of deep Argo float observations.
- A hypothetical extension of drifter data to 150m depth with thermistor chains results in a significant / large improvement to the representation of the near-surface layers. Higher space/time resolution of upper ocean fields is likely required in the future to complement high resolution satellite observations.
- The present tropical mooring array provides invaluable data for evaluation of models and assimilation systems, and provides atmospheric as well as oceanographic data. Assimilation of the ocean data into current ocean model systems has an impact primarily in the region of the moorings.
- Innovative statistical techniques based on neural network methods have been developed to reconstruct pC02 from sparse pC02 in-situ observations and background information (temperature, salinity, mixed layer depth). The techniques were then used to assess the sensitivity of the reconstruction to the in-situ pCO2 networks (vessels, moorings, Argo). It was shown that the existing ship-of-opportunity and mooring network, enhanced by BGC-Argo sampling in the South Atlantic at around one quarter of current physical Argo resolution should allow a large improvement of the pCO2 field there (and thus of CO2 air/sea fluxes and pH). Sampling these regions could be a priority for a BGC Argo pilot experiment in the tropical Atlantic and South Atlantic. Further improvements could be obtained from moorings or Argo coverage in the Labrador Sea, Baffin Bay, Norwegian Sea and African coastal regions between 10°N and 20°S.
- Assimilation of biogeochemical Argo (BGC-Argo) data complements satellite surface colour data by improving model estimates of oxygen, nutrients, carbon and chlorophyll throughout the water column. It also improves surface chlorophyll estimates when satellite colour data are restricted by cloud. Inclusion of BGC sensors on roughly one quarter of the current Argo array (around 1000 floats) provides clear improvements.
- Data assimilation techniques and OSSEs are less mature for BGC observations. Task 1.3 allowed developing these techniques with promising results. It is expected that further improvements to ocean state estimates and BGC OSSEs could be achieved through development of more advanced assimilation schemes. Specific issues for development include optimal assimilation of multiple data types, and assimilation methods specifically designed for use with sparse observation networks.
- Impact of different in-situ observation types in the current global ocean observing system has also been tested with global OSE. Various metrics showed a non-linear degradation of

the analysed ocean state in all observation removal experiments, with Argo showing the strongest impact. Region-wise, the degradation of the ocean state in the Atlantic was more severe than in the other main ocean basins, indicating the strong need for a dense in-situ network in this region. Assessment of bias evolution in the seasonal forecasting system showed that subsurface observations like those from the Argo network are essential to constrain the ocean state, especially in the North-western Atlantic, but there is also sensitivity to the resolution of the assimilation system that has been underappreciated before.

- Observations of ocean heat transport across key latitudes complement observations of OHC, allowing us to understand in greater detail the role of the Atlantic Ocean in climate variability and change. Model studies suggest that monitoring heat transport at both a subtropical (e.g. 26°N RAPID) and a subpolar latitude would be necessary to fully quantify the effect of climate change on the North Atlantic Ocean.

Based on these OSSEs and quantified estimation of impact in integrated modelling and data assimilations, the recommendations for the evolution of the Atlantic observing systems can be summarized as follows:

- Continuity of the present backbone long term ocean observing system including satellite observations (SSH, SST and Ocean Color) and in-situ observing system (Argo, moorings, XBT, research vessels).
- Implement extensions of Argo for physics (temperature and salinity). Deep Argo is a strong priority. The impact is expected to be large and data can be readily used in modelling and data assimilation systems and for climate studies. There is an urgent need to monitor the long term evolution of the deep ocean.
- Implement BGC Argo. Impact will be large both for surface carbon studies and biogeochemistry. A priority could be to start a pilot study in the tropical and south Atlantic. There is a need in parallel to develop further the assimilation of BGC data in models.
- Continue monitoring heat transport at both subpolar and subtropical latitudes.
- Use new techniques (e.g. drifters, saildrones) to provide a higher sampling of upper temperature and salinity fields.
- Impact of glider observations was not assessed as part of Atlantos task 1.3. As soon as there is an agreed long term plan for systematic glider observations in the Atlantic, it will be necessary to assess its value (both for physics and biogeochemistry) through OSSEs. Note, however, that glider observations are not meant to provide basin scale measurements but to focus on specific regions such as western boundary currents and coastal and shelf areas.

Recommendation for future observing design activities and OSSEs:

- Atlantos made major achievements for the development of OSSE activities in Europe. Priorities for future OSSEs should include the development of OSSEs over longer time scales (e.g. 10 years). Assessing the impact of gliders and assessing further the impact of BGC observations are also strong short term / mid term priorities.
- Coordination between modelling/data assimilation experts and observation/network experts is essential for a proper design and interpretation of OSSEs, especially to extract compelling messages on the ability of the ocean observing system to resolve processes

having different space and time scales. User oriented metrics (i.e. based on the foreseen impact on users and applications) should also be developed.

- OSSEs require heavy and dedicated infrastructures (running R&D versions of operational ocean analysis and forecasting systems). It is essential to consolidate and strengthen the capabilities of operational and climate centres to assess the impact of present and future observations (in particular for BGC EOVs) to guide observing system agencies but also to improve the use of observations in models. These activities should be consolidated and developed in Europe, in particular, as part of a partnership between EOOS (European Ocean Observing System) and the Copernicus Marine Service. Cooperation with international partners (e.g. OceanPredict programme) is essential.

AtlantOS Task 1.3 acknowledged publications:

- Hughes, C. W., Williams, J., Blaker, A., Coward, A., & Stepanov, V. (2018). A window on the deep ocean: The special value of ocean bottom pressure for monitoring the large-scale, deep-ocean circulation. Prog. Oceanogr., 161, 19-46. doi:10.1016/j.pocean.2018.01.011
- Hedemann, C., Mauritsen, T., Jungclaus, J., and Marotzke, J. (2017). The subtle origins of surface-warming hiatuses. Nature Climate Change, 7, 336-339, doi:10.1038/nclimate3274.
- Gasparin, F., Greiner, E., Lellouche, J.-M., Legalloudec, O., Garric, G., Drillet, Y., Bourdalle-Badie, R., Le Traon, P.-Y., Remy,E., and Drevillon, M. (2018). A large-scale view of oceanic variability from 2007 to 2015 in the global high resolution monitoring and forecasting system at Mercator-Ocean, J. Marine Syst., 187, 260–276, https://doi.org/10.1016/j.jmarsys.2018.06.015.
- Denvil-Sommer, A., Gehlen, M., Vrac, M., and Mejia, C. (2018). FFNN-LSCE: A two-step neural network model for the reconstruction of surface ocean pCO_2 over the Global Ocean, Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-247, in review.

AtlantOS Task 1.3 submitted publications:

- Garry, F. K., McDonagh, E., Blaker, A. T., Roberts, C. D., Desbruyères, D. G., Frajka-Williams, E., King, B. A. (2018). JGR Oceans, submitted.
- Gasparin F., S. Guinehut C., Mao, I. Mirouze, E. Remy, R. King, M. Hamon, R. Reid., A. Storto, P.Y. Le Traon, M. Martin and S. Masina (2018). Requirements for an integrated in situ Atlantic Ocean Observing System from coordinated Observing System Simulation Experiments, Frontiers in Marine Sciences, In Review.
- Gasparin F., Hamon, M., Remy, E., and P.Y. Le Traon (2018). Towards robust estimations of the deep ocean variability with deep Argo. J. Climate, to be submitted.
- Germineaud C., Brankart J.M. and Brasseur P. (2018). An ensemble-based probabilistic score approach to compare observation scenarios: an application to biogeochemical-Argo deployments, Monthly Weather Review, submitted.
- Fujii, Y., Remy, F., Zuo, H., et al. (2018). Observing System Evaluation Based on Ocean Data Assimilation and Prediction Systems: On-going Challenges and Future Vision for Designing/Supporting Ocean Observational Networks, Frontiers in Marine Science-Ocean observation. Submitted

AtlantOS Task 1.3 publications in preparation:

- Allison, L.C., C.D. Roberts, M.D. Palmer, R. Killick, L. Hermanson, N.A. Rayner and D.M. Smith (2019). Towards quantifying uncertainty in ocean heat content changes using synthetic profiles, in preparation.
- Garry, F. K., Roberts, C. D., Frajka-Williams, E., McDonagh, E., Blaker, A. T., and King, B. A. (2019). Where do we need deep ocean observations to estimate planetary energy imbalance from ocean heat content?, in preparation.
- Ghosh, R., Jungclaus, J., Lohmann, K., Matei, D. (2019). Disentangling the effect of the global warming from the internal variability in the North Atlantic heat transport, in preparation
- Ford, D. et al. (2019). Description of Met Office biogeochemical OSSEs) (in preparation)
- Mao, C., R. King, R. Reid, M. Martin and S. Good (2019). Impact of in situ observations in FOAM: an observing system simulation experiment study. In prep. for JGR Oceans.
- Zuo, H., Balmaseda, M.A., Tietsche, S., Mogensen, K., Mayer, M. (2019). The ECMWF operational ensemble reanalysis-analysis system for ocean and sea-ice: a description of the system and assessment. Ocean Science, in preparation.
- Guinehut, S. et al. (2019) Impact of Argo observing system enhancements in a multi observations ocean state estimate (in preparation).