ASSESSESMENT OF THE IMPACT OF ARGO IN OCEAN MODELS AND SATELLITE VALIDATION FROM E-AIMS PROJECT

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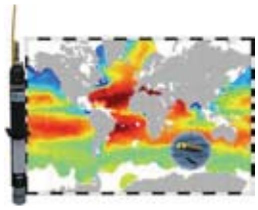


Abstract

The main objective of the E-AIMS (Euro-Argo improvements for the GMES/Copernicus Marine Service) FP7 project is to conduct R&D activities on Argo float technology, Argo data centers and the design of the new phase of Argo (improved coverage, deep ocean, biogeochemical sensors, polar regions) to better answer existing and future needs of the Copernicus Marine Service. Observing System Evaluations and Observing System Simulation Experiments have been, in particular, conducted to quantify the contribution of Argo to constrain global and regional monitoring and forecasting centers and validate satellite observations. Recommendations for the new phase of Argo are also elaborated. A summary of these results is provided here.

Context: the Copernicus Marine Service, Argo and Euro-Argo

The Copernicus Marine Service through its MyOcean projects has set up a pan-European service for ocean monitoring and forecasting over the global ocean and European seas. In-situ and satellite observations are routinely assimilated in ocean models to provide in real time or in delayed mode (reanalyses) integrated descriptions and short-term forecasts of the ocean physical and biogeochemical state. These core products serve a wide range of applications and users. The delivery of the Copernicus Marine Service strongly relies on the timely provision of both satellite and in-situ observations. While satellites provide a global view of the surface of the oceans, in-situ systems provide complementary data primarily by monitoring their interior. In the context of the Copernicus Marine Service, global to regional scale in-situ observations are required to constrain the models at depth & provide calibration and verification data. The Marine Service has thus a very high dependency on in-situ observations.

The international Argo programme is a major element of the global in-situ ocean observing system. More than 3500 floats are now globally measuring temperature and salinity throughout the deep global oceans, down to 2,000 metres and delivering data both in real time for operational users and after careful scientific quality control for climate change research and monitoring. Argo is the single most important in-situ observing system for the Copernicus Marine Service. It provides essential/critical data in near real time to constrain global and regional data monitoring and forecasting centers and to validate satellite observations. Techniques are also mature and fully demonstrated. Float technology will also evolve in the coming years to include new sensors (e.g. oxygen, biology) and new capabilities (e.g. deep ocean, under ice measurements) that are essential for climate change research and for the Copernicus Marine Service.

The Euro-Argo research infrastructure organizes and federates European contribution to Argo (www.euro-argo.eu); it is part of the European ESFRI roadmap on large research infrastructures. Euro-Argo carried out a preparatory phase project, funded through the EU 7th Framework Research Programme, whose main outcome was to agree on the legal and governance framework (Euro-Argo ERIC) under which to establish the research infrastructure. The Euro-Argo ERIC was set up in May 2014; it will allow European countries to consolidate and improve their contribution to Argo international. The main challenges for Argo and Euro-Argo are 1/ to maintain the global array and ensure its long term sustainability and 2/ prepare the next phase of Argo with an extension towards biogeochemistry, the polar oceans, the marginal seas and the deep ocean. Meeting such challenges is essential for the long term sustainability and evolution of the Copernicus Marine Service. This requires major improvements in Argo float technology. New floats with improved capabilities are or will be soon available from float manufacturers. They require, however, extensive testing at sea before they can be used for operational monitoring. The Euro-Argo data centres need also to be upgraded so that they can handle these new floats.

The FP7 E-AIMS project

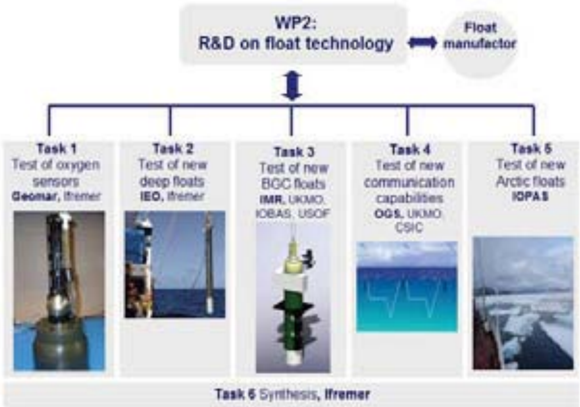
E-AIMS (Euro-Argo Improvements for the GMES/Copernicus Marine Service) is an FP7 Space R&D project dealing with the in-situ component of Copernicus (see www.euro-argo.eu/E-AIMS). E-AIMS is led by Ifremer and gathers 16 institutions from 9 different countries. E-AIMS will organize an end-to-end evaluation of new Argo floats (from float design down to the use by GMES/Copernicus). Observing System Evaluations and Sensitivity Experiments will also be conducted to provide robust recommendations for the next phase of Argo that take into account GMES/Copernicus Marine Service, seasonal/decadal climate forecasting and satellite validation requirements. E-AIMS will thus demonstrate the capability of the Euro-Argo infrastructure to conduct R&D driven by GMES/Copernicus needs and demonstrate that procurement, deployment and processing of floats for GMES/Copernicus can be organized at European level. These are key aspects for the long term sustainability of GMES/Copernicus in-situ component. At the end of E-AIMS, Euro-Argo should agree on and start implementing the new phase of Argo. This requires demonstrating feasibility and utility which is the very objective of E-AIMS.

• Ifremer, France, UKMO, U.K OGS, Italy, NERC/BODC, U.K. KNMI, Netherlands, IEO, Spain, IMR, Norway, USOF, Bulgaria, IOPAS, Poland, Geomar, Germany, Mercator Océan, France, INGV, Italy, CLS, France, ACRI-ST, France, CSIC, Spain, IOBAS, Bulgaria.

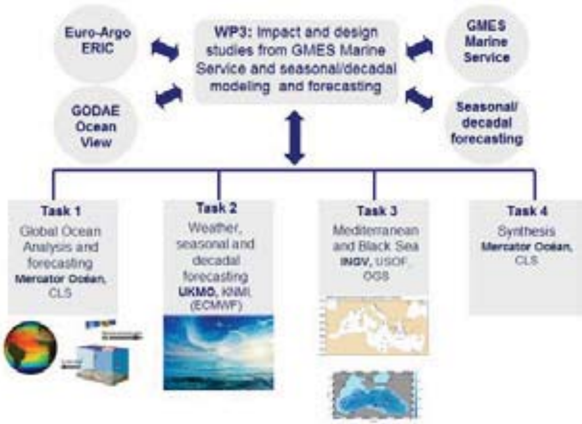
The project started in January 2013 and will end in December 2015. It is organized along the following work packages:

WP1&7, 8: Management, Coordination and Communication

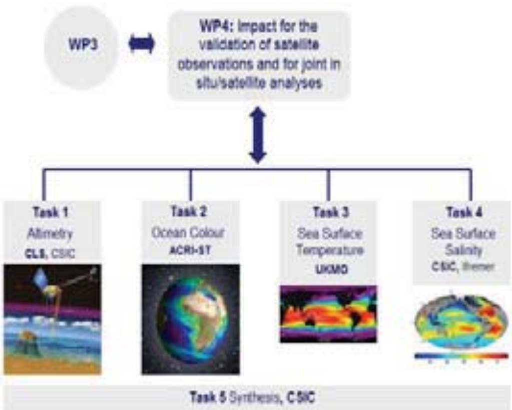
WP2: R&D on float technology. The objective of WP2 is to test several new Argo floats which have been recently developed. These new models of floats require intensive testing before they can be used for operational monitoring. WP2 will organize an end-to-end test of the following new floats: floats with oxygen and biogeochemical sensors, deep floats, floats with improved communication capabilities, Arctic floats.



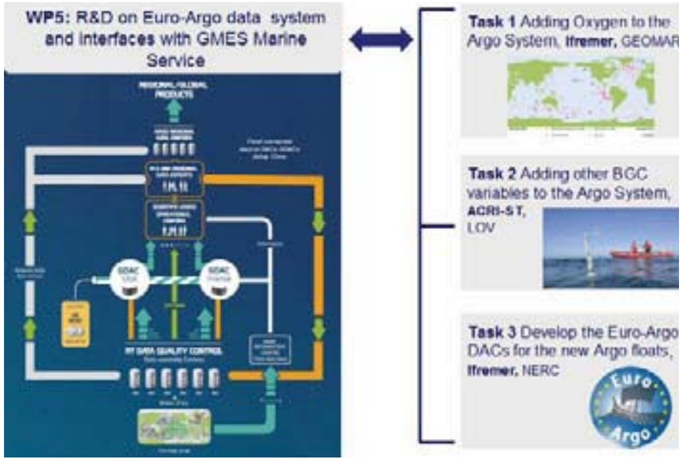
WP3: Impact and design studies from Copernicus Marine Service and seasonal/decadal modeling and forecasting. The main objective is to perform Observing System Experiments and Observing System Simulation Experiment with the Copernicus Marine Service assimilative systems to assess the potential of Argo and its extensions.



WP4: Impact for the validation of satellite observations. WP4 will analyze the use of Argo float data to calibrate, validate and monitor the long term stability of satellite observations. Present and future requirements for satellite Cal/Val activities will be given.



WP5: R&D on Euro-Argo data system and interfaces with Copernicus Marine Service. The objective is to improve the Euro-Argo data system to better serve the Copernicus Marine Service and adapt it to the future generation of Argo profiling floats.



WP6: Real time processing, impact and final assessment. The objective is to demonstrate that Euro-Argo data centers can process in real time the new floats developed and tested in WP2, distribute them to MyOcean modeling and forecasting centers and satellite Cal/Val teams as well as to show that these teams can effectively use these new data sets.

An overview of main results from WP3 and WP4 is given in the next sections focusing on aspects directly relevant to the Copernicus Marine Service. Main recommendations are also given in the final section.

Impact and design studies for Copernicus Marine Service monitoring and forecasting centers

Several impact and design studies were carried out as part of E-AIMS. Main results related to the Copernicus Marine Service monitoring and forecasting centers are given here. Impact of Argo floats have been assessed both at global and regional scales.

Global ocean

1-year Observing System Evaluations (OSEs) were carried out with the Mercator Ocean ¼° global data assimilation system. A reference run where all data (satellite altimetry, sea surface temperature, Argo and other in-situ observations) are assimilated is compared to a run without Argo data assimilation or with only half of the Argo data assimilated. A strong impact of Argo data assimilation is identified on temperature and salinity estimates at all depths, linked with an observation minus model forecast error (innovation) reduction both in term of variability and bias. Through Argo assimilation the differences between observation and forecasted fields is thus reduced by about 20% in the 0-300 m depth and from 20% to 65% in the 700-2000 m layers depth **(Figure 1)**. Argo floats are thus crucial in the system to control the model forecasted water properties, from the surface down to 2000m. Not all regions are equally impacted by the Argo observations. The performance of the system is also degraded if only half of the array is assimilated. Time series of the anomaly of heat and salt content for different depth ranges (not shown here) also reveal a strong sensitivity to the density of the Argo array.

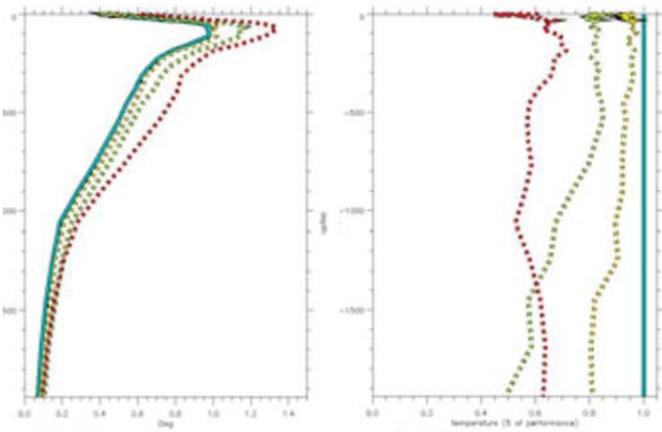


Figure 1: OSEs carried out with the Mercator Ocean global data assimilation system. Vertical structure of RMS of temperature innovations (left) and normalized RMS temperature innovations (right) from 0-2000m for Run-Ref (blue) (all observations assimilated), Run-Argo2 (yellow) (half of the Argo data assimilated), Run-NoArgo (green) (no Argo data assimilated) and Free Run (red). Innovations are defined as observation minus model forecast fields.

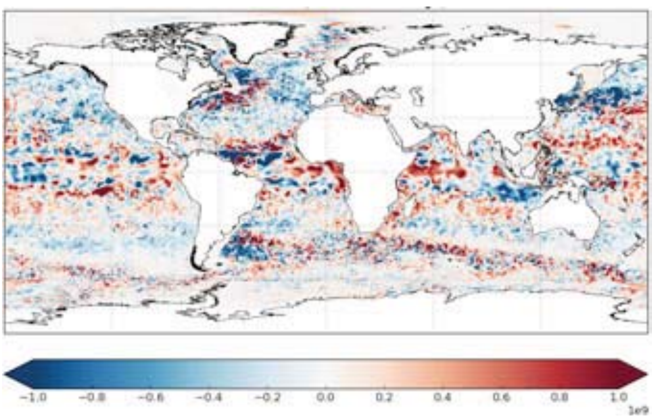


Figure 2: OSEs carried out with the Met Office ocean/atmosphere coupled system. Upper-ocean heat content difference (J, of top 300m) between the control analyses and the no-Argo analyses averaged over October 2012 (control minus no-Argo) global data assimilation system.

ARMOR3D Copernicus Multi Observations system developed by CLS has also been used to assess the impact of Argo observations to map temperature and salinity fields together with satellite observations using Degree of Freedom of Signal (DFS) diagnostics. Results show that most of the information comes from the Argo observing system, with almost no redundancy, then from the satellite dataset (altimetry and SST) and then from the other in-situ instruments (e.g. moorings, XBTs). This demonstrates, once again, the major role played by the Argo observing system.

The denial of Argo observations from the Met Office coupled global data assimilation system caused a similar large degradation in ocean temperature and salinity innovation statistics. The greatest differences in the upper ocean built slowly over 6 to 12 months and future OSEs investigating the impact of Argo and other ocean observing systems should be run for between 6-months and 1-year. **(Figure 2)**. Case study forecasts with the Met Office ocean/atmosphere coupled system of Hurricane Sandy highlighted that the assimilation of Argo profiles has an impact on the analyzed position of the Gulf Stream, with consequent impacts on forecasts. However, no systematic improvements of the atmospheric state can be determined without further case studies. A crucial aspect of the coupled model which is expected to influence forecast skill is the diurnal cycle of SST, and high vertical resolution near-surface data will be useful for the assessment of this aspect of the model. A number of Argo profiles already make this data available, and the extension of this to the whole array would be very useful for coupled forecasting, particularly as the cost of the additional measurements is minimal. High vertical resolution near-surface temperature data from all Argo floats would be required for such an application.

Observing System Simulation Experiments, where observations are simulated from a fully known ocean simulation, were also carried out to simulate extension of the future deep Argo network and its impact on the Mercator Ocean global ocean data assimilation system. The analysis quality at depth greatly benefits from observations deeper than 2000 m, even with a sparser spatial coverage than the surface layers. Deep ocean bias could then be corrected for (Figure 3). The oceans deeper than 2000 m are mainly unobserved as of today and they represent more than 50% of the total ocean volume. Given the role of the deep ocean on the earth climate it is essential to set up a global, long term monitoring system for depths deeper than 2000 m. E-AIMS results show that such deep measurements will be crucial to validate and constrain Copernicus Marine Service models at depth.

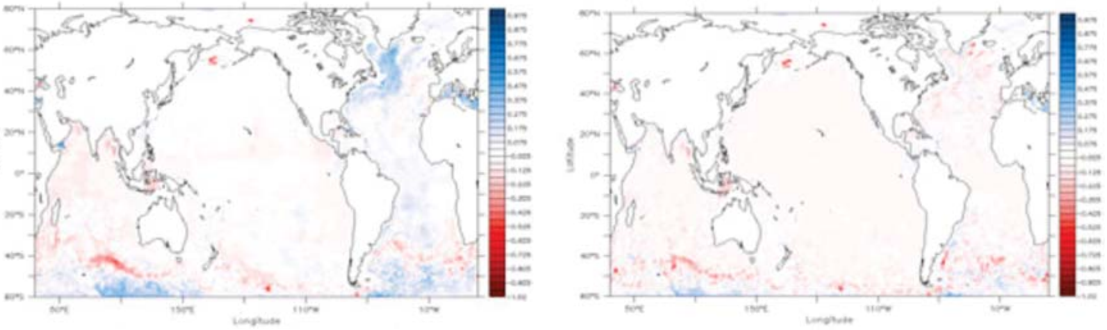


Figure 3: OSSE carried out with the Mercator Ocean global data assimilation model to analyze the sensitivity of results to the assimilation of deep (4000 m) Argo floats. Three month mean temperature difference between the analyzed and the simulated "truth" in the 2000m-4000m layer: on the left without any float diving below 2000 m and on the right with one third of the floats diving up to 4000 m every three 10-day cycle (colour scale between -1 and 1°C).

Mediterranean Sea

INGV studied the impact of the Argo horizontal and vertical/time sampling scheme through both OSEs and OSSEs on the quality of the MyOcean Monitoring and Forecasting Center analyses and forecasts. Argo observations produce a reduction of 30% on RMS of the analysis residual (observation minus model background) for temperature and salinity with respect to the free model simulation. If we use only half the Argo fleet, the mean analysis residual in salinity increases by 30% and the RMS error by 10% in the thermocline. OSSEs evidenced that the Argo sampling scheme could be modified to further improve the operational analyses quality. A positive impact has been found when probes have a drifting time of 3 days (as compared to 5 days) and vertical continuous sampling (every meter for Argo) with respect to vertical subsampling as presently done. Full profile transmission could also be considered as a major improvement for the MyOcean Mediterranean analyses. Results from OGS modelling experiments indicate that the assimilation of floats has a small but positive impact on the biological compartment as well. The improvements are located mainly in specific area (e.g. north western region of Mediterranean Sea) and specific period of the year (e.g. winter) when the vertical mixing is relevant for biogeochemical dynamics.

Black Sea

Experiments with different deployment strategies demonstrated that increasing the amount of Argo floats performs better than increasing the frequency of surfacing. Without Argo data, estimates in the upper mixed layer suffer from large errors. Profiling float measurements are very important for depths below the seasonal thermocline because the transition from thermo-to-haline-dominated stratification shows only short spatial covariance length. Another major conclusion from this research is that the present number of Argo floats operating in the Black Sea of about 10 seems optimal for operational purposes. Further increase of this number could be beneficial when addressing specific research questions.

Use of Argo for satellite validation

The satellite validation studies carried out in E-AIMS have been focused on sea level from satellite altimetry, ocean colour, sea surface temperature and sea surface salinity. It must be noticed that the development stage and maturity of the corresponding satellite missions differ from one to the other. All these satellite missions require, however, to be validated with in-situ measurements and Argo provides unique observations for such a validation. Analyses carried out as part of E-AIMS confirm the high potential of Argo observations for the validation of satellite observations. For some missions (e.g. SSS) they already are the main source of information to validate and monitor the quality of satellite observations. Main findings and results are summarized here:

- Satellite altimetry and Argo are quite complementary. Sea Level Anomalies (SLA) from altimeter measurements and dynamic height anomalies (DHA) calculated from the temperature and salinity profiles of the Argo network are strongly correlated and thus, their comparison can be used to detect drifts, anomalies or jumps in altimeter measurements, assess improvements due to altimetry data process standards, or to detect errors in the Argo float time series. Results indicate that the altimeter drift detection and the global statistics of the differences between altimetry and Argo data are only slightly affected by a reduction of the number of Argo floats and a reduced spatial coverage of the in-situ network while a reduced temporal sampling of the floats (>10 days) could prevent appropriate assessment of the impact of new altimeter standards. Detection of the altimeter drift and the quality assessment of new altimeter standards or products are, however, sensitive to the Reference Depth and would benefit from deeper Argo observations.

- Ocean colour remote sensing data (Chlorophyll-a concentration, Chl-a, and diffuse attenuation coefficient, Kd) and data derived from bio-profilers (i.e., Chl-a and Kd) are indirect measurements relying on semi-empirical models of the backscattered light at the sea surface (remote sensing) and fluorescence (bio-profilers). Direct comparison of two "indirect" sources of observation might therefore allow identifying weakness (or strengths) of both the measurement technology and their semi-empirical transformation. The development of bio-Argo profilers is timely to the calibration/validation of the future Ocean and Land Colour Instrument (OLCI) on board Sentinel 3 planned to launch late in 2015. The ability of bio-Argo floats for the verification of future ocean colour remote sensing missions has been demonstrated through matchups between Chl-a from remote sensing and Chl-a integrated over the upper layer measured by existing bio-Argo floats **(Figure 4)**.

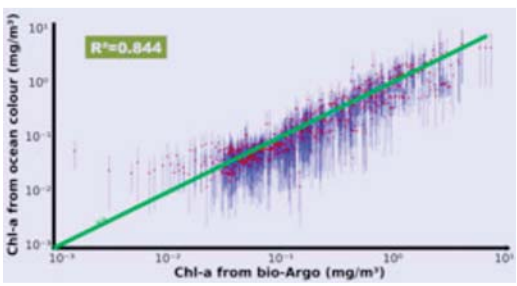


Figure 4: Matchup between bio-Argo and remotely sensed Chl-a estimates.

• Satellite sea surface temperature observations (SST) are obtained from infra-red and microwave sensors. They are generally validated with precise in-situ surface observations (in particular from surface drifters). The global coverage of Argo is now providing a very complementary mean for the validation of satellite SST measurements. Argo observations between 3-5 m have been shown to provide a good estimate of SST when compared to the OSTIA (Operational SST and Ice Analysis) gridded SST (http://ghrsst-pp.metoffice.com/). The sampling error associated with the monthly mean difference between the OSTIA analysis and near-surface Argo observations has been investigated. The monthly total number of near-surface Argo observations is suitable for a sampling error of <0.03 K for most major ocean regions. Some exceptions are western boundary current regions (0.082 K) and the Polar regions (0.2 K). The monthly total number of near-surface Argo observations currently available is sufficient to identify a statistically significant difference in standard deviation between two analyses where large differences have been found. The Pacific has enough observations to demonstrate statistical differences between the analyses. However, more floats are needed in the North and South Atlantic. Routine monthly validation of OSTIA and GMPE SST products using quality-controlled Argo observations from the EN4 database 2 has now been set up. Time series of global and regional statistics (using the MyOcean region definitions) are freely available on the web: http://ghrsst-pp.metoffice.com/pages/latest_analysis/sst_monitor/argo.

• Remotely sensed estimates of sea surface salinity (SSS) can be derived from microwave radiometry at L-band. The Soil Moisture and Ocean Salinity (SMOS) and the Aquarius missions have been the first ones designed to provide operational estimates of the global SSS fields. They have been launched in 2009 and 2011 respectively. As of today, the Argo array is the only observing system able to provide global measurements of salinity, allowing validation of the retrieval algorithms in different geophysical scenarios (sea surface temperature, surface wind speed and distance to the coast). Comparison of Argo near surface salinity data with satellite SSS products generated by the SMOS Barcelona Expert Centre (http://cp34-bec.cmima.csic.es) have demonstrated this high potential of Argo. It has been noticed that the number of available Delayed Mode profiles has been decreasing during the validation period (2011-2013). If in January 2011 more than 6000 Argo salinity profiles are available, by December 2013, less than 1000 Argo salinity profiles are available **(Figure 5)**. This is due to the time required for the Argo data delayed mode quality control but it would be very important to reduce this time delay and/or to produce intermediate data sets where surface observations are validated. The results indicate that robust estimates of the difference between SMOS and Delayed Argo have been found. The standard deviation of the differences are of the order of 0.29 and 0.23 (in the practical salinity scale) depending if the comparison is done in the latitudinal band of 60S-60N or 30S-30N respectively.

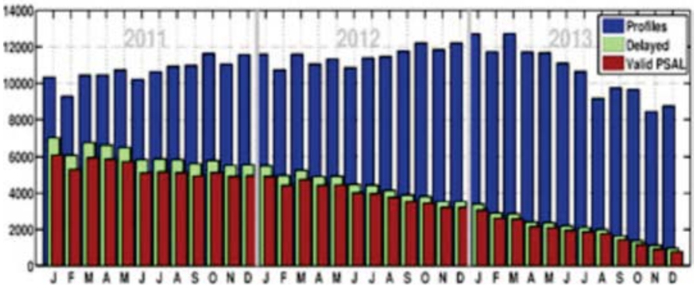


Figure 5: Number of available profiles from January 2011 to December 2013: Shown are the total number of profiles, the delayed mode profiles, and the number of delayed mode profiles with salinity.

Conclusions and recommendations

Analyses carried out as part of E-AIMS confirm the very strong impact of Argo observations to constrain global and regional ocean models. The existing Argo observing system should thus be as much as possible stabilized with its actual spatial and temporal coverage and should continue to equally sample the entire world ocean (a decrease of the number of profiles will immediately lead to a degradation of the ocean analyses and forecasts). There is a strong need of deep Argo profiles (coarse resolution) for model validation and data assimilation. Deep observations are mandatory to monitor and estimate error on forced and assimilative models at large depths.The assimilation of simulated deep Argo floats shows that deep model bias could be corrected for even if the float sampling is coarse. For the upper ocean and for ocean/atmosphere coupled systems, there is a need of higher resolution close to the surface. Other requirements include the continued production of delayed-mode high quality processing of Argo data with minimal time delay (to be used for ocean reanalyses). Optimal drifting time and parking depth are still under investigation and will depend on the regions. In parallel, work should be carried out to improve data assimilation schemes to better use the present Argo profile observations and the future deep/high vertical resolution observations. Although this was not evaluated per se as part of WP3, Bio-Argo data will also be essential to validate Copernicus Marine Service global and regional biogeochemical models and, if the sampling is sufficient, to constrain them through data assimilation. There is now a critical lack of biogeochemical observations and this strongly limits our ability to validate Copernicus Marine Service biogeochemical models.

The results of the satellite validation activities suggest that current spatial and temporal coverage of Argo array is suited for validation activities of sea level, SST, Ocean Colour and SSS (especially for monthly validation). However, further improvements that will help to improve the robustness of these validations are: 1) Speeding up the scientific validation of Argo data; 2) increase the depth of the vertical sampling; 3) increase the number of measurements in the upper four meters of the ocean; 4) increase sampling in regions of high variability; 5) network coverage should be enlarged in the Atlantic Ocean and at high latitudes. Bio-Argo profilers are already a unique source of observations for the validation of ocean colour satellites. Development of this new capability will require on the longer run to: 1) Optimize the match-up strategy; 2) program high-frequency profile cycles when located in a biologically stable area; 3) Make use of additional recoverable profilers at launch and recovery times.

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