E-AIMS

Euro-Argo Improvements for the GMES Marine Service

PROJECT FINAL REPORT

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MAIN S & T RESULTS/FOREGROUNDS

The project started on January 1st 2013 and ended on December 31st 2015. The kick off meeting was organized in Brest in January 2013. A steering committee was organized in June 2013 in Southampton. A specific WP3 workshop was held in September 2013 in Toulouse. The first annual meeting, first annual review and 2nd steering committee took place in Brussels in January 2014. The 3rd steering committee meeting was held in Brest on June 2014. A WP3&WP4 final workshop was organized in Toulouse together with a GODAE OceanView/CLIVAR international scientific workshop in December 2014. The 2nd annual meeting and the 4th steering committee meetings were held in Paris in January, 2015. The 5th steering committee meeting was held in Barcelona in May 2015. The final project meeting and review was finally organized in Brussels in November 2015. All meeting minutes and presentations are available on the E-AIMS internal WWW site.

Work has been performed according to plans and all planned deliverables were issued. Management, scientific coordination and communication activities (WP1, 7 & 8) included preparation and running of annual meetings, annual reviews and steering committee meetings including writing meeting minutes, annual report preparation, interaction with REA, interaction with the Euro-Argo ERIC organization, interaction with MyOcean project, Copernicus Marine Service and Mercator Ocean (EU delegated entity for the implementation of the Copernicus Marine Service), discussing with stakeholders (GMES/Copernicus bureau, EEA, DG Research, EuroGOOS) and development and maintenance of the E-AIMS WWW site (internal and external). These activities have been carried out in close cooperation with the Euro-Argo ERIC management board and program manager. Communication activities have included the preparation of leaflets on each of WP2 Tasks as well as a summary of main WP3/WP4 results. All these leaflets are available on the external E-AIMS WWW site. Short float stories were also integrated in the Euro-Argo educational WWW site in January 2015. A project brochure was prepared and completed in November 2014. It provides a description of the project and its workpackages with illustrations based on results and activities carried out during the first half of the project. A final brochure that detailed the main achievements of the project was finally produced.

Project activities and achievements are detailed for each of the work packages below.

WP2 R&D on float technology

(WP leader: partner 1, Ifremer, France)

The WP2 was organized along five tasks dedicated to test new floats. The first task had to test a new oxygen sensor by comparing it with the sensor which has been already used on floats for several years. The second task had to deploy two deep floats with 4000 m depth capability. The purpose of the third task was to test floats equipped with bio-geochemical sensors in three different areas. The aim of task 4 was to test four floats equipped with new satellite system capabilities (Iridium and Argos-3) for the transmission of the profile data and the possibility to receive remote commands thanks to the downlink. The fifth task had to test floats fitted with surface ice detection capabilities in order to operate in Arctic area by postponing data transmission in case of ice detection.

At the end of the five experiments, a sixth task had to present the main findings of task 2.1 to 2.5, to discuss feasibility and readiness issues for operational monitoring with these new Argo floats and to provide recommendations for future technological R&D activities for Euro-Argo.

Overview of at sea experiment progress

First of all, a description of the objectives of the different experiments and implementation issues were provided in the T0+10 month deliverables: floats to be used, initial sensor check / calibration, specifications of the mission, deployment plan, reference measurements.

Then all the floats were purchased except one deep float (IEO, T2.2). Five types of floats, manufactured by three companies, were funded by E-AIMS (see figure 2.0.1): The Arvor (NKE) and the Navis (Seabird) for task 2.1, the Deep-Arvor (NKE) for task 2.2, The "Bio-Argo CTS4" (NKE) for task 2.3, The Navis and the Arvor for task 2.4 and the Nemo (Optimare) for task 2.5. Two additional Apex (Teledyne) floats (non E-AIMS funding) were also tested in task 2.4 as well as three Deep Arvor (NKE) for task 2.2.

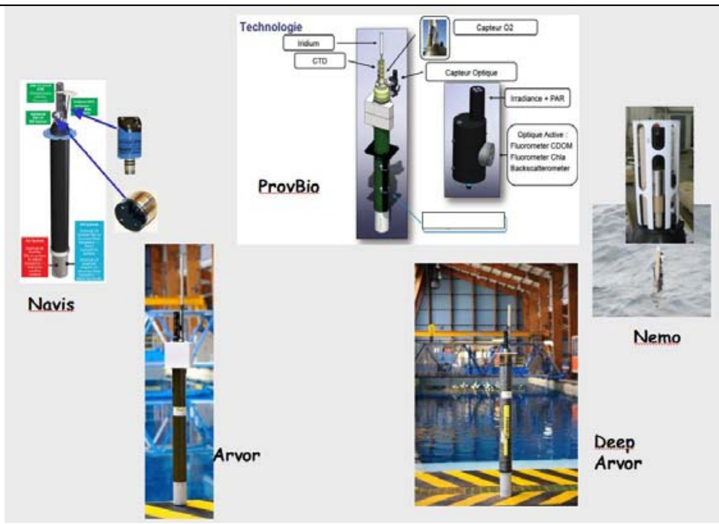

Figure 2.0.1: Presentation of the new floats tested at sea (funded by E-AIMS)

Several geographical areas were chosen for these experiments, depending on scientific interests (figure 2.0.2). The main deployments were carried out in 2013. Remaining floats were deployed in 2014 and 2015 (figure 2.0.3). The deployments took more time than initially planned. This was explained by several factors: the delay in availability of a few floats from the manufacturers, the need to do extra testing on floats, the requirement to find the best cruise offering the possibility of conducting scientific complementary measurements at deployment, or the need to return floats to the manufacturers for repair. Thanks to a careful organization, however, all the planned experiments were carried out with an excellent scientific return.

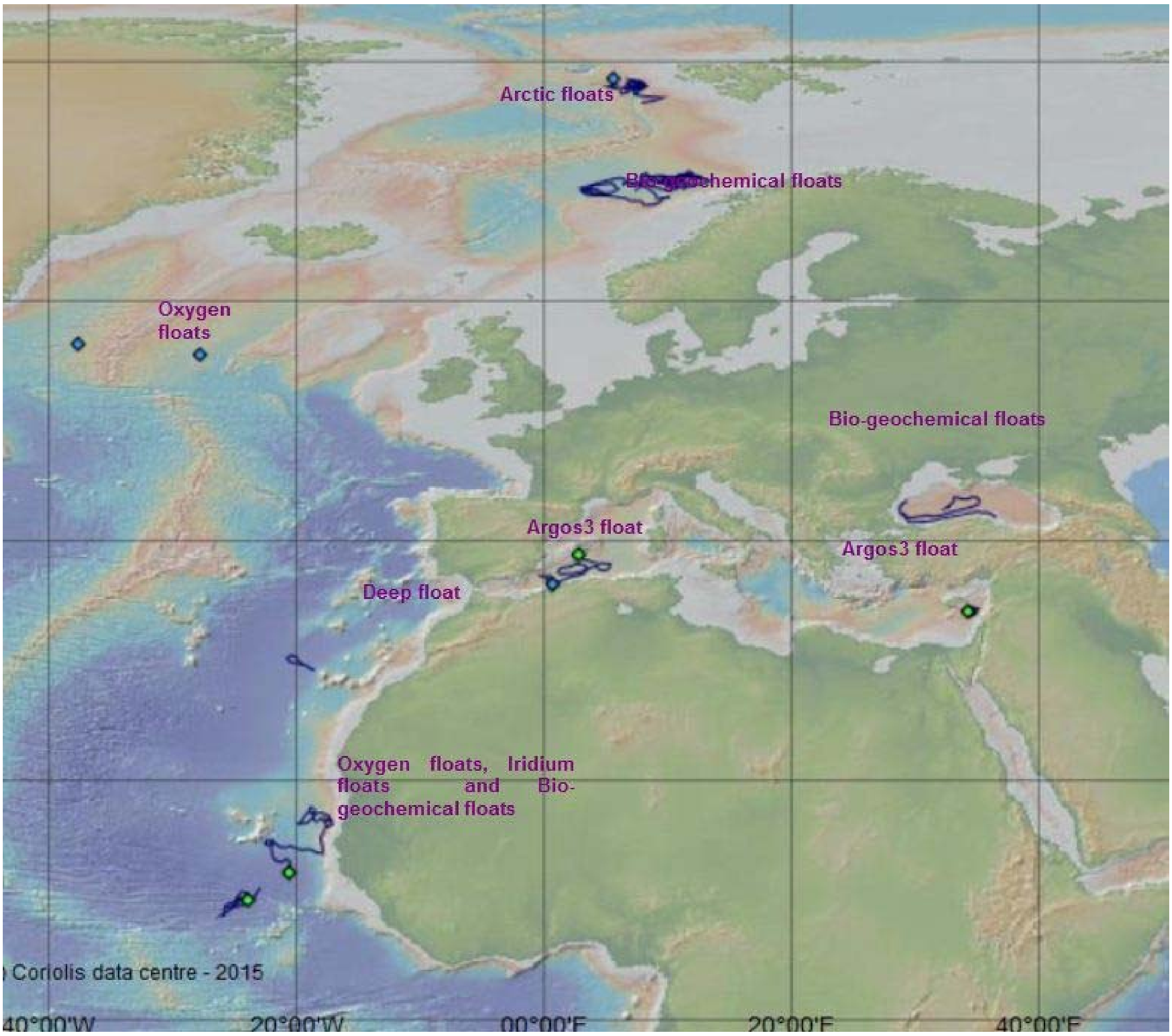

Figure 2.0.2: Map of the deployed floats

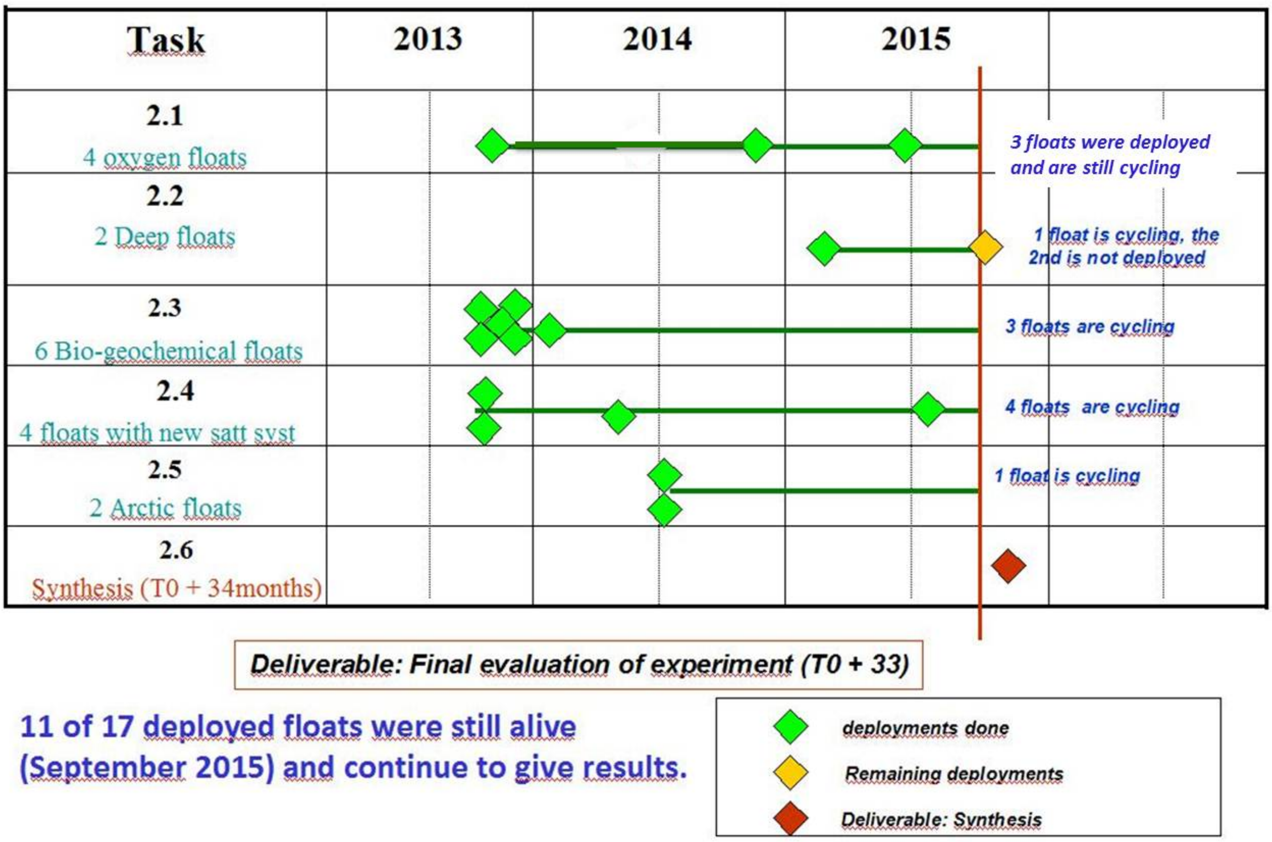

Figure 2.0.3: Deployment status of E-AIMS WP2 floats. The deployments took place between the end of 2013 and the middle of 2015.

Detailed results for each of the five experiments are given in the following WP2 deliverables:

1. E-AIMS_D2.212. Oxygen sensor and float experiment final evaluation.
2. E-AIMS D2.222. Deep float experiment final evaluation.
3. E-AIMS_D2.232 Biogeochemical float experiment final evaluation.
4. E-AIMS_D2.242. Improved satellite communication final evaluation.
5. E-AIMS_D2.252. Arctic float final evaluation.

Main results and conclusions for each of WP2 tasks are summarized below:

Task 2.1: Test of new oxygen sensors: Geomar and Ifremer

The purpose was to compare the performance of the Aanderaa optode (model 4330) and the Seabird optode (SBE63). The two sensors were mounted on three Navis floats (Seabird manufacturer) and two Arvor floats (NKE Manufacturer). The Navis floats were deployed in the OMZ region (off West African coast), whereas the Arvor floats were launched in the North Atlantic. All the sensors were calibrated thanks to in-situ measurements at deployment.

The two Navis floats (figure 2.1.1) and one Arvor float showed very good results after several months of working at sea. However, the SBE63 sensor of the first Arvor failed during the first descent at depth (the float was recovered in September 2015) and some random troubles were sometimes encountered on the SBE63 (invalid measurement readings) and on the 4330 optode (measurement spikes). The oxygen measurement drifted during the months before the deployment of the float, showing that in-situ calibration was essential.

Figure 2.1.1: Navis float equipped with SBE63 sensor and 4330 optode.

The SBE63 is integrated in the pump flow path of the CTD. It exhibits a better time-response than the 4330 and better renders the gradients in the profile. Overall, however, the effect is small. Its stability was not evaluated because it cannot measure in air, but the difference between it and the 4330 increased over the time, probably due to differences in the foils preparation which are pre-aged by Aanderaa.

Oxygen measurements were made in air with the Aanderaa optode 4330. This was used for calibration (Bittig and Körtzinger, 2015) of the sensor who demonstrated that, combined with pressure correction for oxygen optode calculations (Bittig *et al*, 2015), it considerably improved the data accuracy and the stability of the data.

These experiments demonstrated that by making reference measurements at deployment, implementing an in-air measurements routine (figure 2.1.2) and by taking into account a few minor improvements, both floats fitted with the 4330 optode can lead to a fully operational solution for Argo. This could also be the case in the future, if in-air measurement and pre-aging of the foils can be performed with the SBE63 optode. This is a major result of the work carried out as part of E-AIMS.

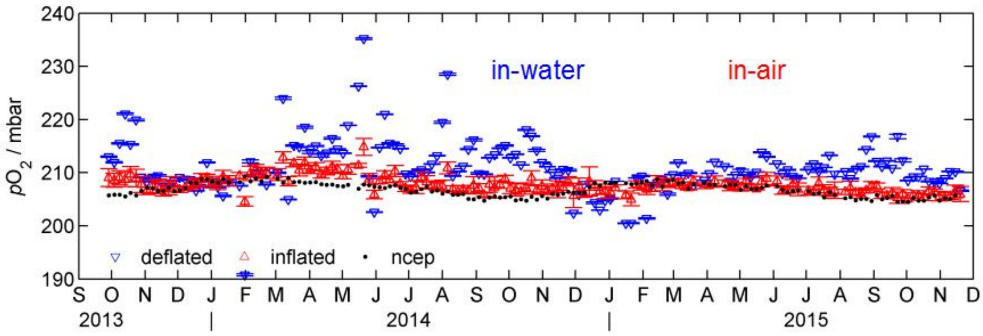

Figure 2.1.2: F0272 in air-optode 4330 measurements time series. Systematic dependence on water supersaturation: in-air measurements as continuous calibration reference.

This work also showed high quality observations in an Oxygen Minimum Zone (OMZ) and contributed to the on-going pilot study in the North-Atlantic and thereby fills gaps in the global Argo Array. It also led to three scientific papers on the use and interpretation of oxygen measurements on Argo floats.

Task 2.2: Test of New deep floats: IEO

The objective of this task was to test a float that was able to perform profiles down to 4000m depth (twice the regular Argo floats depth). The new "Deep-Arvor" model from NKE was used, fitted with a SBE 41CP-CTD. Only one float was purchased in January 2015. The purchase order of the second float was still in progress in autumn 2015.

The float was deployed at the station 24 of the IEO's national ocean observing system at the Canary Islands which has been sampled, since 2006, on March 3rd 2015 and reference measurements were done contiguously. By early November, the float had done 51 profiles at 4000 dbar (cycling mainly every five days). There is a good reproducibility of the float behavior. The regularity of the cycles along time, the stability of the float at parking depth and the quality of data transmission are very satisfying. The analysis of the satellite communication shows that the system spends less than five minutes to transmit a low resolution profile (~200 CTDO samples). The total time spent at surface, including buoyancy management, is approximately 35 minutes.

The temperature measurements are accurate and no drift in time was observed. However, from the first profile, an evident fresh bias salinity (-0.24 PSU) is observed and a drift in time (0.0003 PSU/day). According to the manufacturer, this bias could be due to technological issues on the conductivity sensor: a degradation of the "platine-black" coating of the cell could lead to such a bias. Note, however, that after correction of salinity drift, 0.0074 PSU variability was found during the 10 months of data, which is a similar variability found during 20 years of measurements in the area. IEO has a planned cruise in February 2016, when the float could be recovered. Although the recovery would be after the end time of the project, it would be valuable information in order to improve the performance of the floats.

To complete this analysis, results of another experiment that used three Deep-Arvor floats (NAOS French project) were used. NAOS Deep Arvor floats have had excellent behaviors (capacity to do reproducible cycles with same performance, including grounding management). A particularly impressive result was obtained: one of the float achieved 142 cycles between 3500 to 4000 m with oxygen measurements and with its CTD pump running continuously (life time expected is 150 cycles with CTD only).

Concerning the salinity sensor issue, in the NAOS experiment and like in the E-AIMS one, we noticed that a high fresh bias (~ -0.4 PSU) was observed on one float at cycles 29 and 30, before losing it at cycle 32. Moreover, salinity biases of about 0.01 psu could also detected. These were not pressure dependant and thus could be easily corrected. Such results were also noticed by Jamstec on their trial with the Deep Ninja profiling floats equipped with the same CTD.

The agreement between the voltage drop for the Deep Arvor and the model based on the voltage drop for the standard Arvor 2000 dBars floats demonstrates that the life of the Deep Arvor is proportional to the vertically climbed km. Using this model, it is possible to estimate the decrease in lifetime expectancy for a Deep Arvor based on the number of deep (4000 dBars) profiles.

The experiments demonstrated that the Deep Arvor float is performing very well and salinity data can be corrected. However, Seabird is strongly encouraged to help users resolving the issue of this 0.01 constant bias and to understand the high bias observed on the E-AIMS float CTD sensor.

Concerning the sampling, the recommendations is to perform at least one deep 4000 dbar profile every five standards 2000 dbar profiles, in order to sample properly the scales in the deep ocean and avoid aliasing. This sampling scheme will improve the lifetime of the Deep Arvor float (150 cycle's capability if profiling at 4000m). If compared with the standard 2000 dBars Arvor floats, this would lead to imply a reduction in the lifetime expectancy of 17%. Note that in area where deep water masses are subject to large spatial and interannual variability, as in the in the North-Atlantic or Southern oceans, the sampling rate should be increased to 1 profile every 10 or 15 days.

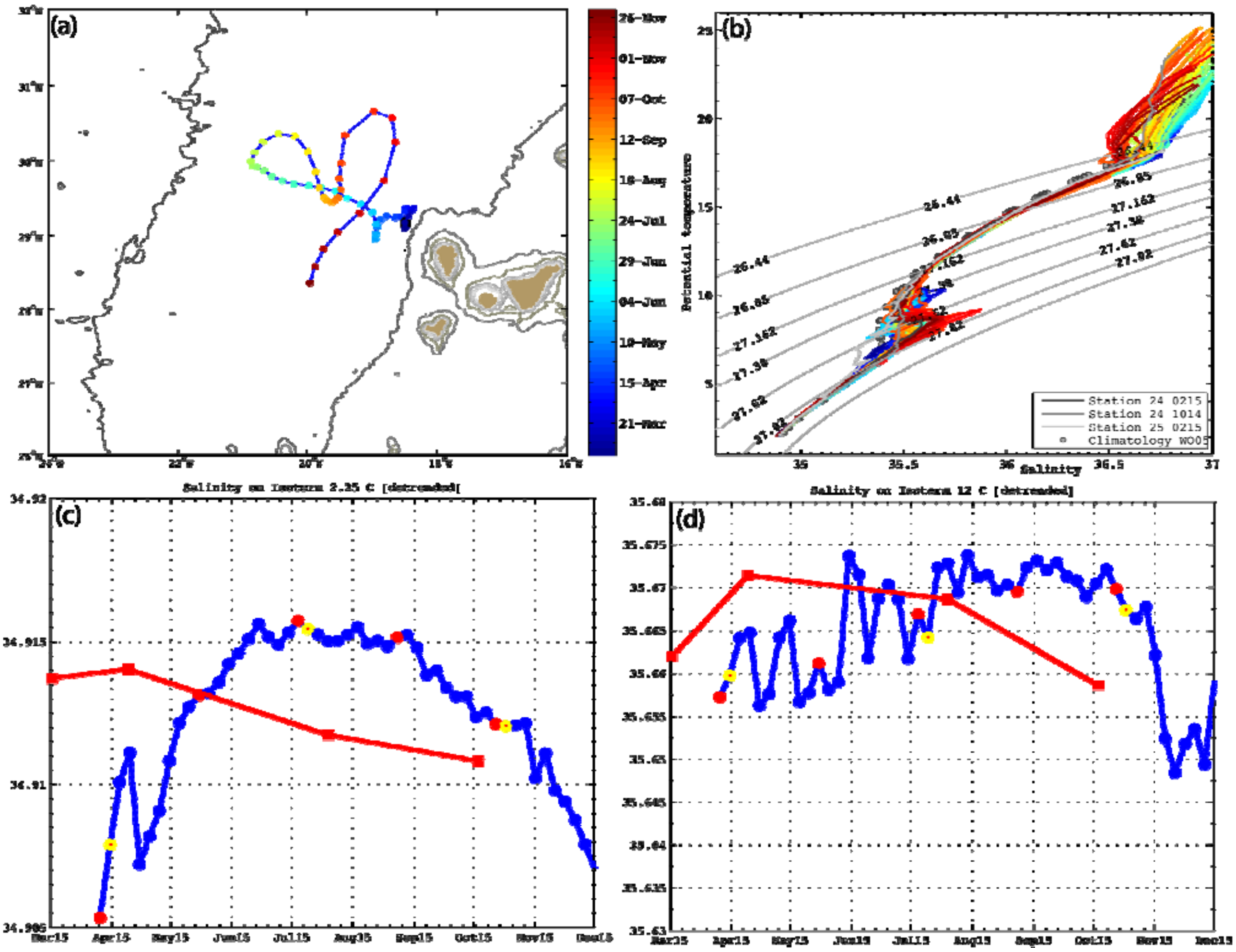

Figure 2.2.1: (a) trajectory of Deep Arvor float WMO6901246 (b) Potential Temperature / salinity diagram after calibration (c) Salinity on the isotherm 2.25ºC (approximately 3480 dBars), blue dots are observations of the Deep Arvor every five days; red dots are observations of the Deep Arvor subsampled every 50 days (one every five standard argo profiles), yellow dots are observations of the Deep Arvor subsampled every 100 days (one every ten standard argo profiles).The red squares are the SBE911 CTD observations (d) as (c) but just for isotherm 12ºc (approximately 540 dBars).

Task 2.3: Test of new geochemical floats: IMR, UKMO/PML, IO-BAS/USOF

The purpose was to test six Argo floats equipped with new bio-geochemical sensors. Three experiments were conducted in three different areas: Atlantic Ocean off West African coasts, Black Sea and Nordic Seas. The float chosen for this experiment was the Provor named "Bio-Argo CTS4" manufactured by NKE, equipped with the Seabird 41CP for pressure, salinity, temperature, an Aanderaa optode 4330 for dissolved oxygen and a Satlantic optical pack named "Rem-A" for irradiance, Chl-A and backscattering. Figures 2.3.1, 2.3.2 and 2.3.3 illustrate oxygen measurements, backscattering and Chl-A results.

The temperature and salinity measurements performed well, but one Wetlabs ECO-triplet failed at the fourth cycle, when it was exposed to pressures greater than 1000 dbar, and remained failed. This sensor was also affected by some instrumental drift and /or bio-fouling effects. A decrease of two oxygen measurements was also revealed at parking depth, suggesting a drift of the optode and large peaks were observed on Chl-a at parking depth, but were unlikely caused by a sensor issue.

From the scientific outcomes aspects, this experiment showed that the biogeochemical floats deliver novel data that improve our understanding of the biogeochemical ocean, but has also pointed few questions that need further investigations. The data from these floats have also already been used in several other studies which also have resulted into submitted peer-review manuscripts.

Even though all of our bio-geochemical floats do not work at this day, several significant results have shown that this technology is mature for the Bio-Argo needs. Among the six floats deployed in 2013, four of them have worked two years and three are still working. The batteries embedded in the floats are well adapted to cover all the requirements (cycling, acquisition of all the sensors, transmission of the data). The deployment phases were successful since all the floats performed at least one cycle. The transmission system has performed well: no loss of data was mentioned and remote commands were successfully sent to the floats. However, two floats were affected by intermittent failures in GPS reception and the ECO-triplets sensors were subject to significant instrumental drifts and one failed.

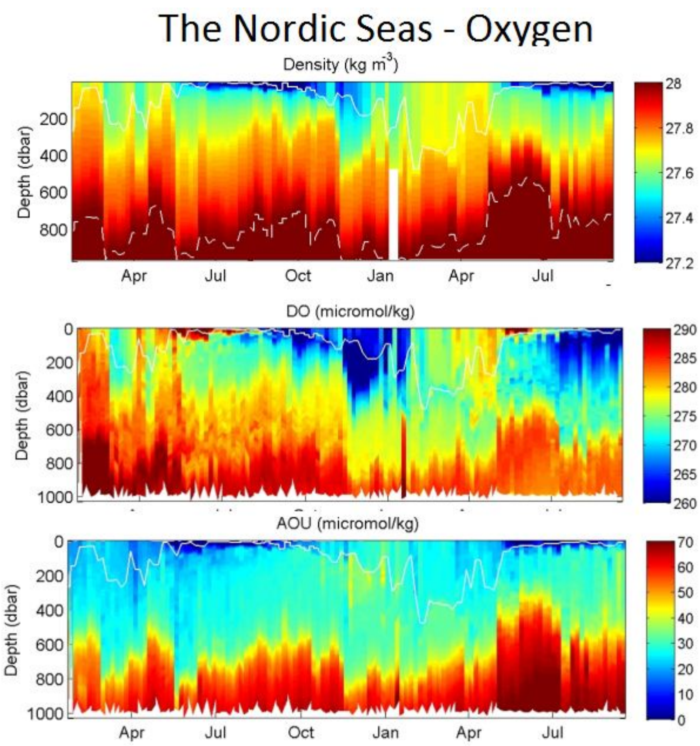

Figure 2.3.1: Density dissolved oxygen and apparent oxygen time series (AOU = $[02]_{sat}$-[02]), Jan2014-Sept2015).

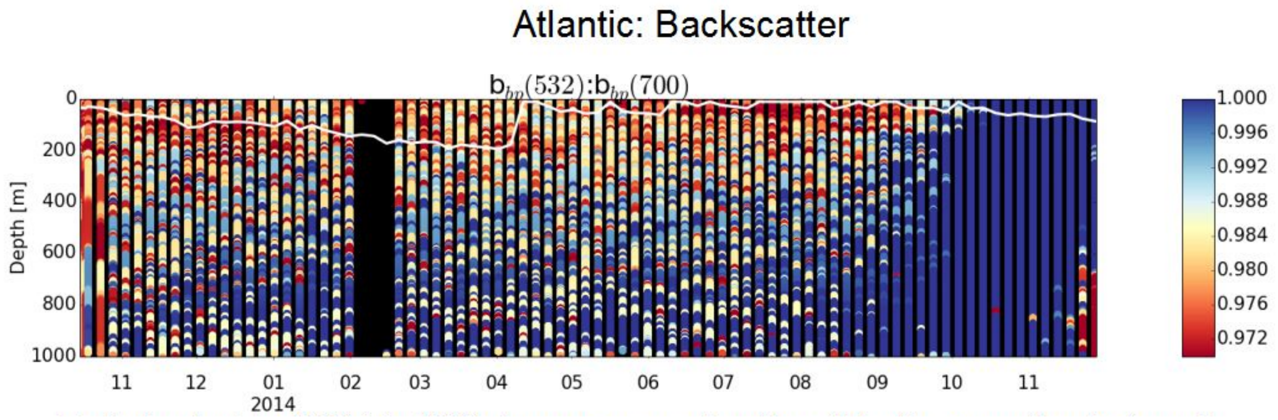

Figure 2.3.2: To first order bbp(532):bbp(700) decreased as a function of depth suggesting that small particles become more abundant in the mesopelagic zone.

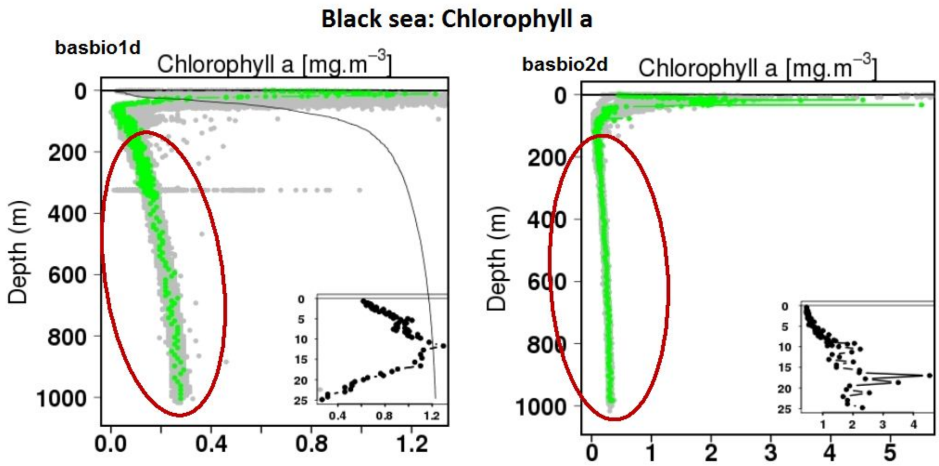

Figure 2.3.3: The gradually increase in chl-a with depth is not understood. It could be insufficient calibration of the sensor or its malfunction in the H2S environment, or that the Chl-a sensor reacts to other substances (for example yellow substances or bacteria).

Except the issue of the GPS reception of the float itself, the main recommendations are directed to the sensors improvements or handling. Tests of the ECO-triplet before delivery (pressure withstanding, calibration and stability, sensitivity) should be done by the manufacturer Satlantic/ Wetlabs. On-going discussions are engaged with the manufacturer with respect to these various issues. Pre-deployment controls should be done (e.g tests and calibrations of sensors for comparison with that from the manufacturer). If possible, relevant in-situ (ship) measurements during deployment are also desirable. If no in-air measurements are available, deep measurements and the calculation of the "apparent oxygen utilization" can be used for the dissolved oxygen drift assessment. The programming of the float mission by users and the method to correct drifts may influence the results (e.g use of bbp data for corrections). Further investigations should be useful to explain the slightly increase in the calculated Chl-a (sensor or environment effect?).

Task 2.4: Test of floats with Iridium and Argos-3 transmission capability: OGS/CSIC, UKMO

The purpose was to test floats equipped with Iridium and Argos-3 satellite communication systems. Using such systems allow transmitting a data profile in a short time, in order to reduce surface risks (such as biofouling, drift, thefts, etc). Moreover, these new generations of satellite systems allow the user to send remote commands to the floats and to change their mission configuration.

Four floats (two Navis + two Arvor) funded by E-AIMS, and two additional Apex floats were used. The Navis and the Apex worked with Iridium ("Rudics" mode) transmission system, whereas the Arvor used the third generation of the Argos system.

The Iridium floats were deployed in October 2013. When this float surfaces at the end of a profile, the float acquire a GPS fix, uploads its hydrographic and engineering data, and downloads any changes to its mission parameters. For both the Apex and Navis floats, such changes can be achieved by placing an updated mission configuration file on the host server.

The two Argos-3 (interactive low data rate mode) floats were deployed in the Mediterranean Sea in 2014 (see Argos-3 float trajectory in figure 2.4.1) and 2015. The float arrives at surface at a time in accordance with the ephemerides of the Argos satellite passing. Then, data are uploaded and commands are downloaded at the same time. The positioning is done with the Argos system itself. Changes of mission parameters are done via sending commands through the CLS-Argos website.

The whole of E-AIMS fleet was still working in September 2015.

The profiling floats demonstrated the Iridium RUDICS system is operational. The utility of this mode of transmission has been proven at sea for high resolution profiles, where Argos and Iridium-SBD modes are too restrictive. The demonstration of their uplink and downlink capabilities was done successfully. To be fully integrated in the Argo data processing chain, the problems encountered in the data processing at BODC have to be solved (in progress). These trials showed the importance of the validation of the remote commands before sending them to the float, with a utility onboard the float, in order to avoid conflict or hazardous programming.

The profiling floats fitted with Argos-3 proved to be operational in the low data rate mode. The downlink capability has been demonstrated to change the mission configuration. A typical Argo dataset can be transmitted in a few minutes, where more than eight hours were required with the Argos-2 generation. However, eight percent of the profiles are not located. This issue can be addressed by selecting satellites passes with an elevation lower than 80° or 85°, by changing this parameter with the downlink.

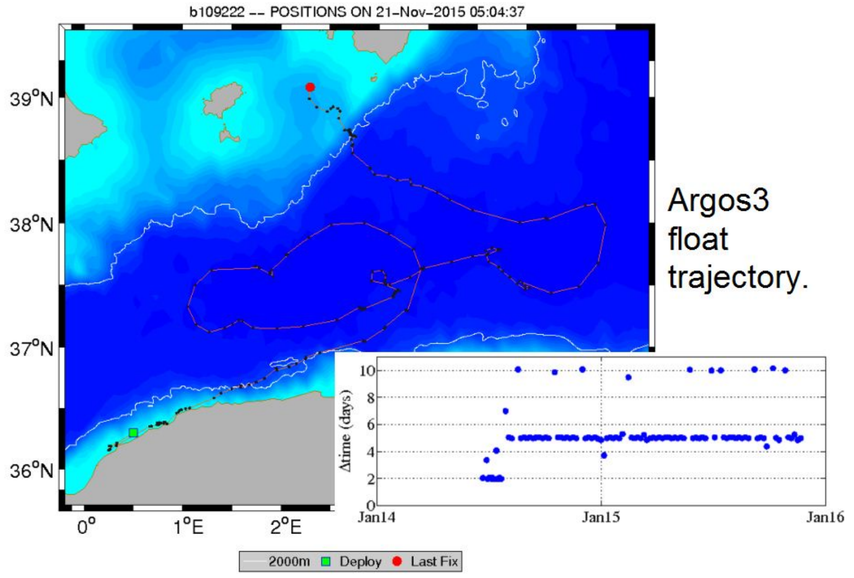

Figure 2.4.1: Argos-3 float trajectory. All profiles dataset were transmitted in only one satellite pass, in about three minutes. The cycling period of two days was successfully changed to five days using the Argos-3 downlink.

RUDICS transmission systems are well adapted when a high quantity of data is requiring: high resolution profiles, multi-sensor profiles. Argos-3 may be used to transmit standard Argo profiles in marginal seas (where it is essential to shorten the stay at surface) as an improved solution compared to Argos-2, or as an alternative way to Iridium. A paper was published about Argos-3 embedded on floats (André *et al*, 2015).

The satellite communications technologies are evolving, and new ones are coming. The Argo community should remain up-to-date and close to these technologies in order to evaluate the opportunity to implement them on the profiling floats in the future.

Task 2.5: Test of new Artic floats: IOPAS

Two Nemo floats, manufactured by Optimare, were used for this Arctic experiment. They were fitted with a shorter antenna for satellite communications and a protection against shocks when the float ascent under Ice. Avoiding contact with ice was done by the so-called algorithm ISA (Ice Sensing Algorithm) coupled with a data transmission postponing if ice was detected. IOPAN developed an Inertial Navigation System (INS) using recent advances in miniaturization of MEMS technology in order to assess the possibility of navigation during immersion. One of the two floats was used to embed the INS. The two floats were deployed in summer 2014 (see Nemo floats trajectory in figure 2.5.1).

One float encountered technical problems, and sent incomplete data 59 days after its deployment and then disappeared. However, the second float had sent data from 83 profiles and 16 datasets from the INS at the end of June 2015, and was still working in early November 2015 (109 profiles) where it was situated not far from the Arctic Ocean drifting sea ice.

The energy consumed by the INS was higher than expected and it was decided to switch off the navigation system several weeks, ~80 km drift after deployment. This was made by the Iridium downlink. The INS returned mostly zeros and incorrect numbers, incompatible with the surfacing positions of the float. Most likely, the accuracy of the sensors was not sufficient to provide good information about the instrument displacement.

This experiment shows that one float survived in the harsh environment of these regions; even though it did not encounter ice covered areas.

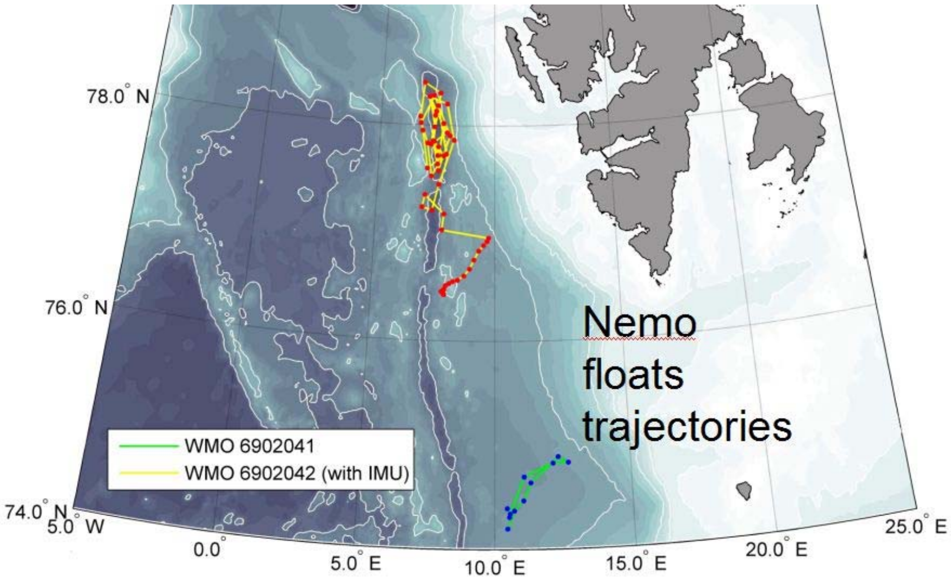

Figure 2.5.1: Nemo float trajectories.

The technology to allow inertial navigation on floats is not mature as expected. Today, there is no solution that satisfies at a time the accuracy needs, the mechanical size, the energy consumption, the cost. However, efforts should be continued to get an alternative way for under-ice navigation.

Sophisticated floats, with more sensors or devices, need better capacity batteries but high energy densities, and particularly Lithium batteries, are expensive and difficult to transport. The costs of Arctic experiments by floats are rising, similarly to gliders, because they need a permanent supervision by a staff.

Another idea is to construct new, less sophisticated and cheaper floats, assigned for short missions. This type of float should be designed for missions shorter than one year, for operation in shallow waters (big part of the Arctic Ocean and subarctic seas are shelves). Compact construction (spherical shape?) should prevent from getting damaged by floating ice or getting stuck on bottom. A simple cheap electronic module should contain the bathymetry map, which would also help in preventing contact with the bottom. Floats for shallow seas must meet very similar conditions, and efforts towards constructing a cheap float for the Arctic and shallow seas should be joined. Such floats may be much more attractive for potential users. By using both types of floats (sophisticated ones for long missions under sea ice and cheaper ones for short missions in ice free regions) may improve coverage of the Arctic by the Argo floats.

But only a revolution in the development of efficient, stable and cheap sources of energy will enable using all the technological advances, such as the active ice and bottom detection, inertial navigation, wide spectrum of sensors, big amount of data processed by intelligent floats.

General conclusions

These experiments were very helpful for the assessments of new floats, new sensors, new devices and new methods. Even though some of these experiments were shortened, they were carried out over several months on average and more than two years for the major part. Early November, 11 of 17 deployed floats were still active.

Overall WP2 achieved or even exceeded all its initial objectives. Highly valuable results have been obtained. Task 2.1 showed that oxygen measurements could be considerably improved by adding in-air measurements when the float is at surface and that thanks to these improvements operational monitoring of oxygen with Argo float can now be implemented. Task 2.2 assessed the performance of new deep floats. It showed that deep floats are ready for operational implementation but it also highlighted the issue of the quality of sensor measurements in the deep ocean. The successful test of six Bio-Argo floats within the task 2.3 demonstrated the maturity of the float technology, even though some work remains to be done on validation of the different sensors. The two satellite communication systems tested in task 2.4 demonstrated the feasibility and benefits of these improved telecommunication techniques; the evolution of these satellite systems towards new capabilities should be considered in the future. The test of Arctic floats showed the difficulties encountered and the technological and financial limitations to navigate in ice covered regions. Finally, several of the WP2 results led to peer-reviewed publications.

WP3 Impact and design studies from Copernicus/GMES Marine Service and seasonal/decadal modeling and forecasting

(WP leader: partner 11, Mercator Ocean, France)

The main objective of WP3 is to perform Observing System Experiments (with real data) and Observing System Simulation Experiments (simulate and assimilate observations to test new observing capacities with the GMES/Copernicus Marine Service assimilative systems to assess the potential of Argo and its extensions.

WP3 is divided into 4 tasks:

- Task 3.1 led by Mercator Ocean is dealing with the global uncoupled prediction system.
- Task 3.2 led by the Met Office is dealing with coupled prediction systems (from days to decades).
- Task 3.3 led by INGV is dealing with regional (Mediterranean and Black Sea) analysis and prediction systems.
- Task 3.4 led by Mercator Ocean and CLS will synthetize the results. A final workshop has been organized jointly with GODAE OceanView and CLIVAR GSOP.

The total duration of WP3 is 24 months. The deliverables have been scheduled as follows. For all regions (Global, Mediterranean and Black seas) and all applications:

- T0+3: Initial requirements (April 2013).
- T0+9: OSE/OSSE plans (October 2013).
- T0+21: OSE/OSSEs results and recommendations (October 2014).
- T0+24: Final report (December 2014).

Initial requirements and OSE/OSSE plans have first been documented. The work then carried out is summarized hereafter and includes the following tasks:

- ✓ Conduct OSEs (Observing System Evaluations) to estimate the role of the current Argo floats in different type of analysis and forecasting services (R/T forced and coupled, seasonal and decadal).
- ✓ Simulate pseudo-observations mimicking the future possible deployment of new Argo floats, conduct OSSEs (Observing System Simulation Experiments) in different context of analysis and forecasting services (R/T forced and coupled, seasonal and decadal).

- ✓ Synthetize the different experimental results to draw recommendations on the Argo array evolution in the framework of analysis and forecasting services.

The WP3 (and WP4) final workshop was organized in December 2014 jointly with GODAE OceanView and GSOP/CLIVAR international meeting in Toulouse (see photo below).

Figure 3.0.1: Attendees of the workshop (https://www.godae-oceanview.org/outreach/meetings-workshops/task-team-meetings/OSEval-TT-Workshop-co-located-with-E-AIMS-and-GSOP/)

Task 3.1: Impact of Argo on the Mercator Ocean global ocean analysis and forecasts

Impact of Argo on Mercator Ocean global ocean analysis and forecasts

The sensitivity of the global ¼° Mercator Ocean analysis and forecasts to Argo float assimilation is assessed with a series of OSEs and OSSEs.

We have finalized the analysis of the OSE experiments and a scientific paper was written and will be soon submitted the Ocean Science journal. OSSEs were also carried out to test the impact of deep Argo measurements in the framework of a global eddy-permitting ocean analysis and forecasting system.

The 1-year OSE experiments on the Argo current array impact on the global ¼° ocean analysis shows that the present spatial coverage allows a significant reduction of the model-observation misfit at all depths up to 2000 meters compared to a simulation without Argo data assimilation. A reduction of only half of the floats degrades significantly the results. Figure 3.1.1 presents the mean RMS error profile for those different OSE experiments. The results are also compared to an experiment where only the altimeter and SST observations were assimilated and to an experiment without any data assimilated (figure 3.1.1).

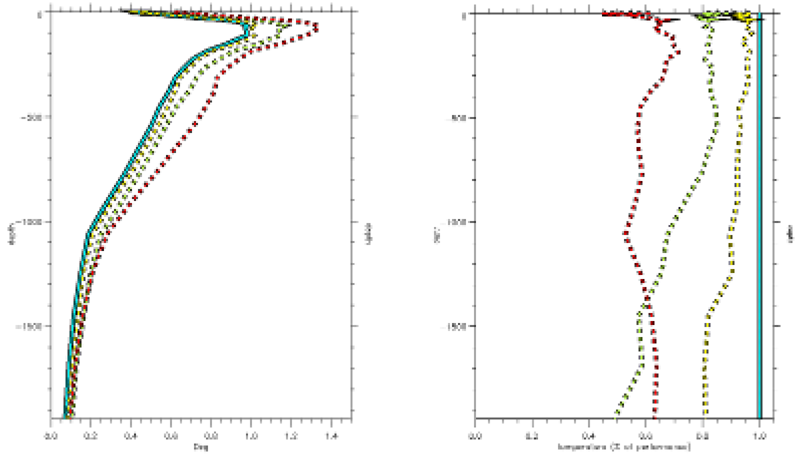

Figure 3.1.1: Vertical structure of RMS of temperature innovations (left) and normalized RMS temperature innovations (right) from 0-2000m for Run-Ref (blue), Run-Argo2 (yellow), Run-NoArgo (green) and Free Run (red).

Keeping only half of the Argo floats is not sufficient at all depths to have a good estimation of the temperature and salinity fields. A strong impact is also seen on heat and salt content estimation. This later quantity is of primary importance in multi-year climate related ocean reanalyses.

The OSE experiments thus show that a sparser spatial coverage of the Argo array than the present one will lead to a degradation of the global ¼° analysis and forecasts of the Mercator Ocean system. The Argo floats are crucial in the system to control the water properties, especially at depth up to 2000m. Below 2000 m the lack of observations does not allow us to estimate the quality of our analysis.

1-year OSSEs were also prepared and conducted. Such experiments allow a full 3D comparison between the "true" simulated ocean and the estimated fields after assimilation. The in situ observations were simulated using a 1/12° global forced simulation. The 2009 Argo coverage was simulated with all profiles extending to the ocean bottom. Then several OSSEs were performed to test the impact of deep Argo floats up to 4000 m and 6000 m depth and their density on the global ¼° ocean forecast and analysis system. We simulated an Argo observation array with all floats going to 2000 m depth, to simulate the present situation; we then expanded the assimilated profiles up to 4000 m depth for all the floats. We also simulated the case were only a one third of the floats will make measurements up to 4000 m (or 6000 m), and only one over third profiles. The density of observation between 2000 m and 4000 m was then reduced by a factor of 9. We only assimilate the in situ simulated observations to focus on their contribution without introducing the problem of the coherency between the sea level observation and the in situ observation, both of them constraining the dynamic height in different ways.

These OSSE experiments show the ability of the current system to assimilate deep profiles up to 4000 m depth. The large biases simulated at depth are reduced compared to an experiment with float profiles going up to 2000 m depth only (figure 3.1.2). A sparse coverage, simulated with keeping only one over nine float profiles up to 4000 m depth appears to be efficient as the space and time scales in the deep ocean are large.

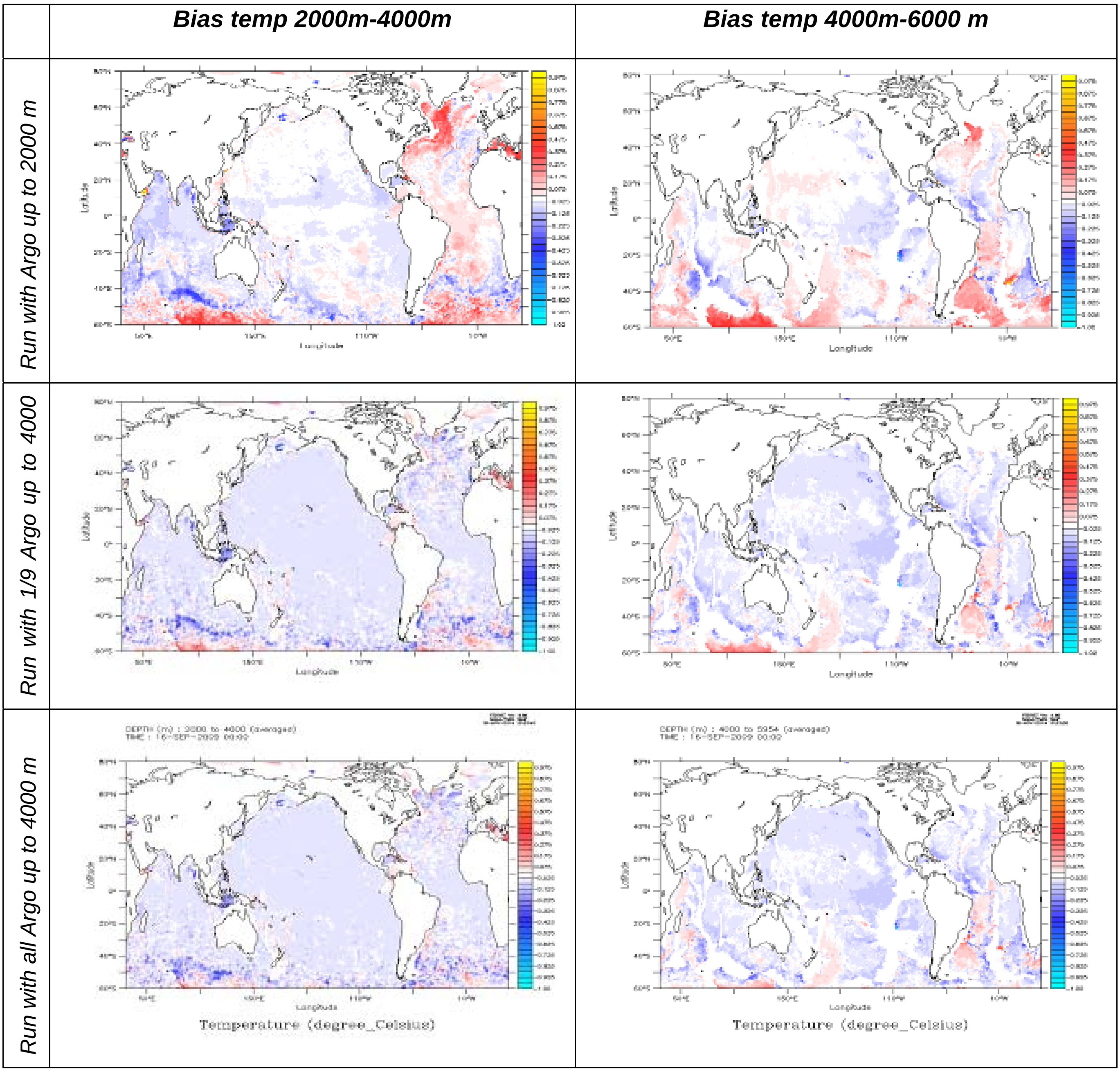

Figure 3.1.2: Mean deep ocean temperature errors in the different OSSEs for two different depth ranges: 2000-4000 m (left) and 4000-6000 m (right).

Main conclusions are as follows:

- ✓ Increasing the depth of Argo floats profiles up to 4000 m depth instead of 2000 m reduces the bias between 2000 up to the bottom where it was large,
- ✓ Increasing the depth of Argo floats profiles up to 4000 m depth instead of 2000 m for only 1/9 of them gives comparable results than if all are going up to 4000 m. This is consistent with the fact we found a low temporal variability but significant bias in some regions.
- ✓ Increasing the depth of Argo floats profiles up to 6000 m depth instead of 2000 m for only 1/9 of them degrades the model solution. This shows that our present system is not tuned

to handle observations up to the bottom. A deep bias slowly appears under 4000 m depth and reach 0.5°C after one year simulation.

Those conclusions are based on model simulation only. As models themselves are poorly validated at depth due to the lack of observation, these results should be taken with some caution.

Impact of Argo on CLS multivariate data analysis system

CLS has developed a multivariate data analysis system that merges satellite (altimetry and sea surface temperature) and in situ observations (Argo, moorings, CTDs, XBTs, etc) through linear regression and optimal interpolation (ARMOR3D system described in Guinehut *et al.*, 2012). This observation-based system is the result of more than ten years of work during which OSE and OSSEs have been conducted (Guinehut *et al.*, 2002; Guinehut *et al.*, 2004; Guinehut *et al.*, 2012).

The ARMOR3D observation-based system is used as part of E-AIMS to assess the impact of Argo observations to map temperature and salinity fields with satellite observations using Degree of Freedom of Signal (DFS) diagnostics. DFS is an influence matrix diagnostics that provides a measure of the gain in information brought by the observations. Several experiments have been conducted and two DFS metrics have been studied.

When two datasets are considered: in situ (including Argo, XBTs, moorings,...) and satellite, results for the temperature field at 100 m and the 1993-2012 period show that for the global ocean, 1/3 of the overall information comes from the in situ dataset at the beginning of the period and that this number increases to 2/3 when the Argo observing system is fully deployed. The satellite dataset completes the information with 2/3 at the beginning of the period and then 1/3.

When three datasets are considered: Argo, other in situ (including XBTs, moorings,...) and satellite, results for the temperature field at 100 m and the 2008-2009 period show that for the 65°S-65°N area, most of the information comes from the Argo observing system (67 %), then the information comes from the satellite dataset (21 %) and finally from the other in situ instruments (11 %) (figure 3.1.3). Almost no redundancy is found in the Argo dataset, apart from the Bay of Bengal and the very west part of the tropical Pacific Ocean where the density of Argo network is very high. Redundant information is found in the other in situ dataset in the three tropical oceans and in the Gulf Stream and Kuroshio regions. This dataset nevertheless complement well the Argo observing system in mid latitude regions. For the satellite dataset, only 20 to 30 % of the information content is exploited by the ARMOR3D method meaning that most of the information is lost because of duplicate data and high measurement error.

Results vary slightly between the surface and 1500 m depth but main conclusions still remain. Moreover, it has been showed that a better representation of the errors on the synthetic fields (i.e. satellite dataset) induces a more realistic vertical structure of the results.

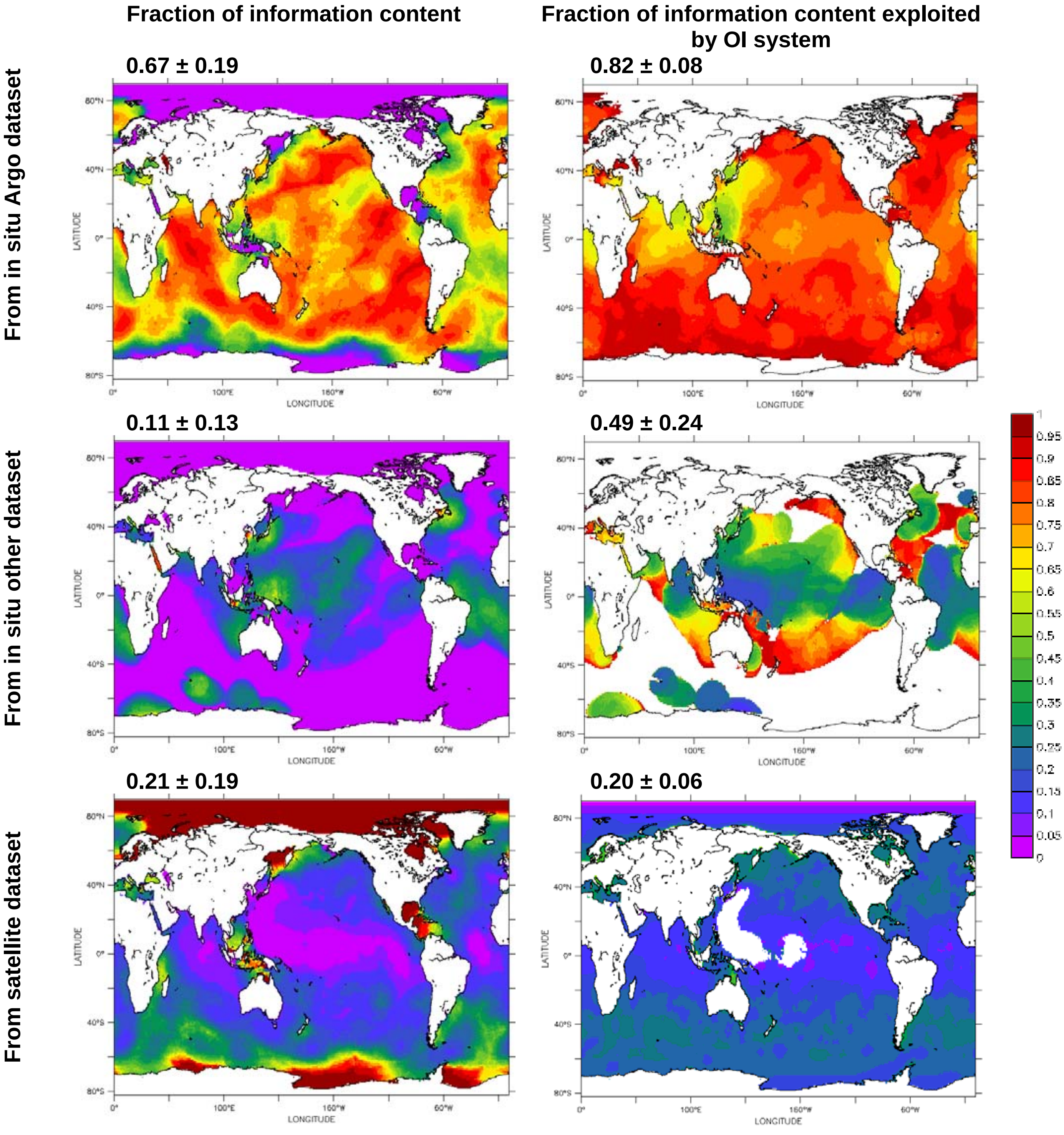

Figure 3.1.3: DFS metrics for the T field at 100 m of the 04/06/2008 analysis - 65°S-65°N means +/- 1 std are also indicated (Units: x100%).

Recommendations

Results from these works show that:

- ✓ the existing Argo observing system should be as much as possible stabilized,
- ✓ the Argo observing system should continue to equally sample the entire world ocean,
- ✓ the existing spatial and temporal coverage of Argo network should be at least maintained,

- ✓ deeper measurements are needed to control model temperature and salinity fields. 1/3 of the floats profiling up to 4000 m one cycle over three would already very significantly reduce biases in model deep fields.

Task 3.2: Weather, seasonal and decadal forecasting (Task leader: UKMO)

Weather and seasonal forecasting - (UKMO)

We have used an observing system experiment (OSE) and two Observing System Simulation Experiments (OSSEs) to investigate the effect of assimilating Argo profiles in coupled analyses and short-range forecasts using the Met Office weakly-coupled data assimilation system. As with all observing system experiments, the impacts shown here are specific to the forecast model, data assimilation system and observations used. The results cannot necessarily be generalised to other systems, but apply only to our prototype weakly-coupled data assimilation system.

An analysis of the ocean innovation statistics (figure 3.2.1) has shown that removing the assimilation of Argo profiles from our system causes a large degradation in the temperature RMS error throughout the sub-surface water column and an increase in the bias, especially near the thermocline. A similar degradation in the salinity RMS error is seen throughout the water column as there are no additional surface observations with which to constrain salinity. The greatest differences in the upper ocean seem to build over the first 6-months, but it is not clear if the full effects are realised by the end of the 13-month runs. Consequently, any OSE run over a shorter period is likely to under-estimate the impact of profile assimilation, especially for the deeper ocean.

A similar analysis of the atmosphere observation-analysis statistics showed negligible systematic global impacts on the atmospheric analyses. However, this was not unexpected due to the continued assimilation of all available atmosphere and sea surface temperature observations in both experiments. On the other hand, case study forecasts of Hurricane Sandy highlighted that the assimilation of Argo profiles has an impact on the analysed position of the Gulf Stream (as seen in figure 3.2.2), with consequent impacts on forecasts after the hurricane passes over the Gulf Stream. Although no systematic improvements in the position or intensity of the hurricane were found in a comparison against the available observations, it was noted that there was a better agreement between the control forecast tracks at different lead-times than for no-Argo forecast tracks. This is potentially a consequence of the broadly lower upper-ocean heat content seen in the control experiment, relative to the no-Argo experiment, as shown in figure 3.2.3.

The results of the OSE indicate that the current Argo network can have an effect on the atmosphere leading to impacts on forecasts in specific case studies. However, results from our OSSEs indicate that there is a substantial amount of work necessary before we could make use of the extra information gathered by a greatly expanded Argo array. The OSE and OSSEs run here have been useful in further highlighting possible deficiencies in the balance involved in the assimilation of both altimeter and profile observations. The OSSEs, in particular, have also highlighted a problem in making use of a higher density of profile observations than is currently available. Although a greater density of observations should allow an improved estimate of the ocean state, and hence improve forecasts, such observations will not have an immediate impact without more effort to improve the assimilation. Given the proposed increase in profile density in particular regions, this will need to be addressed in the near future.

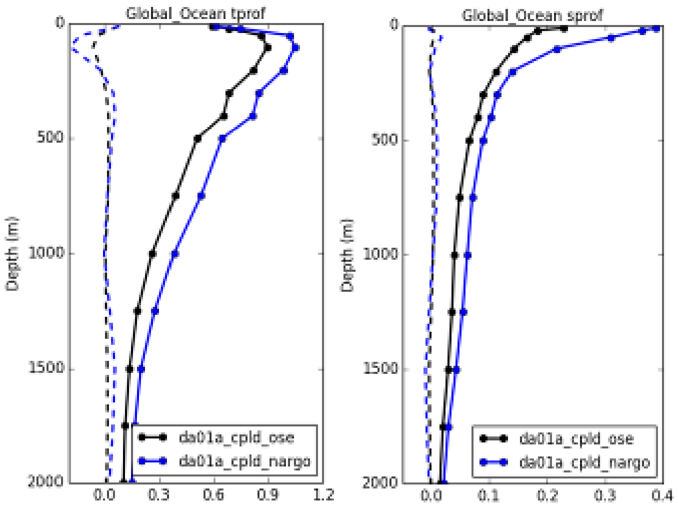

Figure 3.2.1: Global temperature (left) and salinity (right) profile innovation statistics (RMS error shown as solid line, mean error shown as dashed line). The black lines show the statistics over the 13-month experiment for the control run and the blue line the statistics for the no-Argo run.

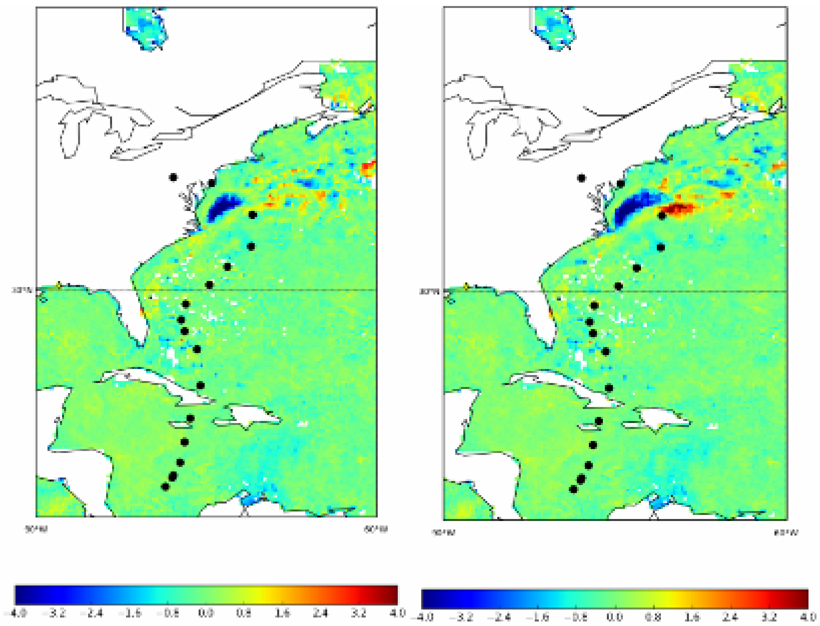

Figure 3.2.2: The mean SST observation-background differences binned to 0.25º for the control (left) and no-Argo experiment (right) over the period 22-30 October 2012. The best-track positions of Hurricane Sandy are show every 12 hours from 12Z on 22-10-2012 to 12Z on 30-10-2012

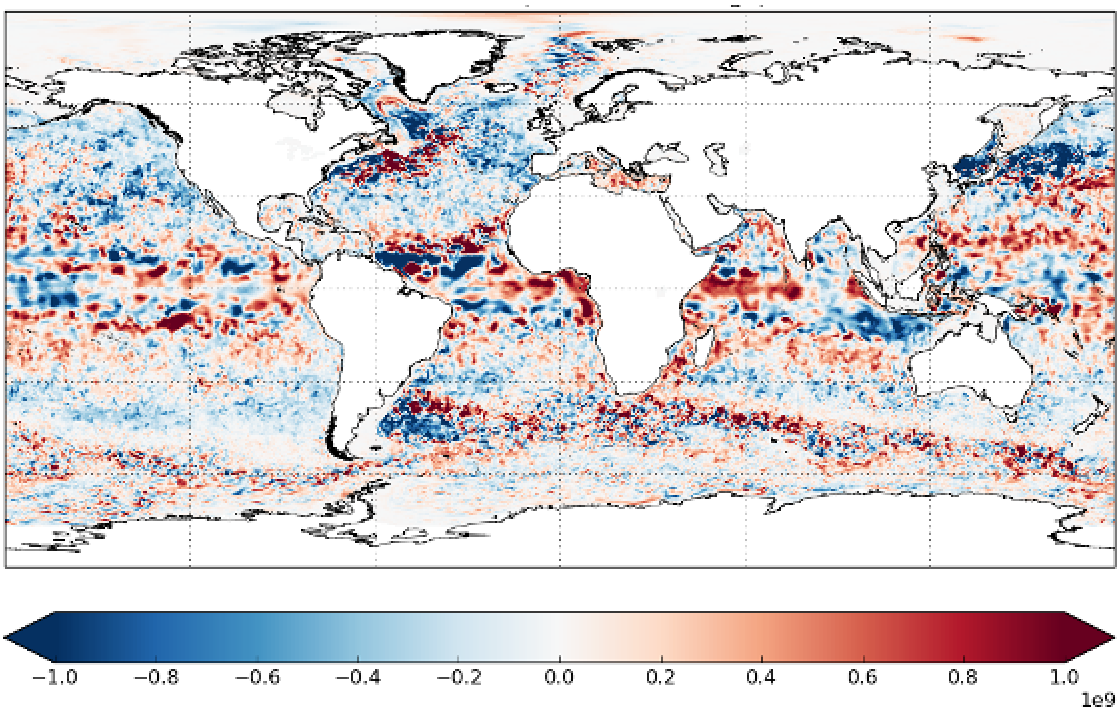

Figure 3.2.3: Upper-ocean heat content difference (J, of top 300m) between the control analyses and the no-Argo analyses averaged over October 2012 (control – no-Argo).

Decadal forecasting time-scales – (KNMI)

The aim of this research was to investigate the impact of the geographic distribution of observations on the skill of decadal climate forecasts by artificially changing the initial conditions. However, hardly any impact was found. Model behaviour is dominated by a large initial drift which is common to all runs. We therefore decided to investigate the drift in more detail. The analysis is limited to the North Atlantic.

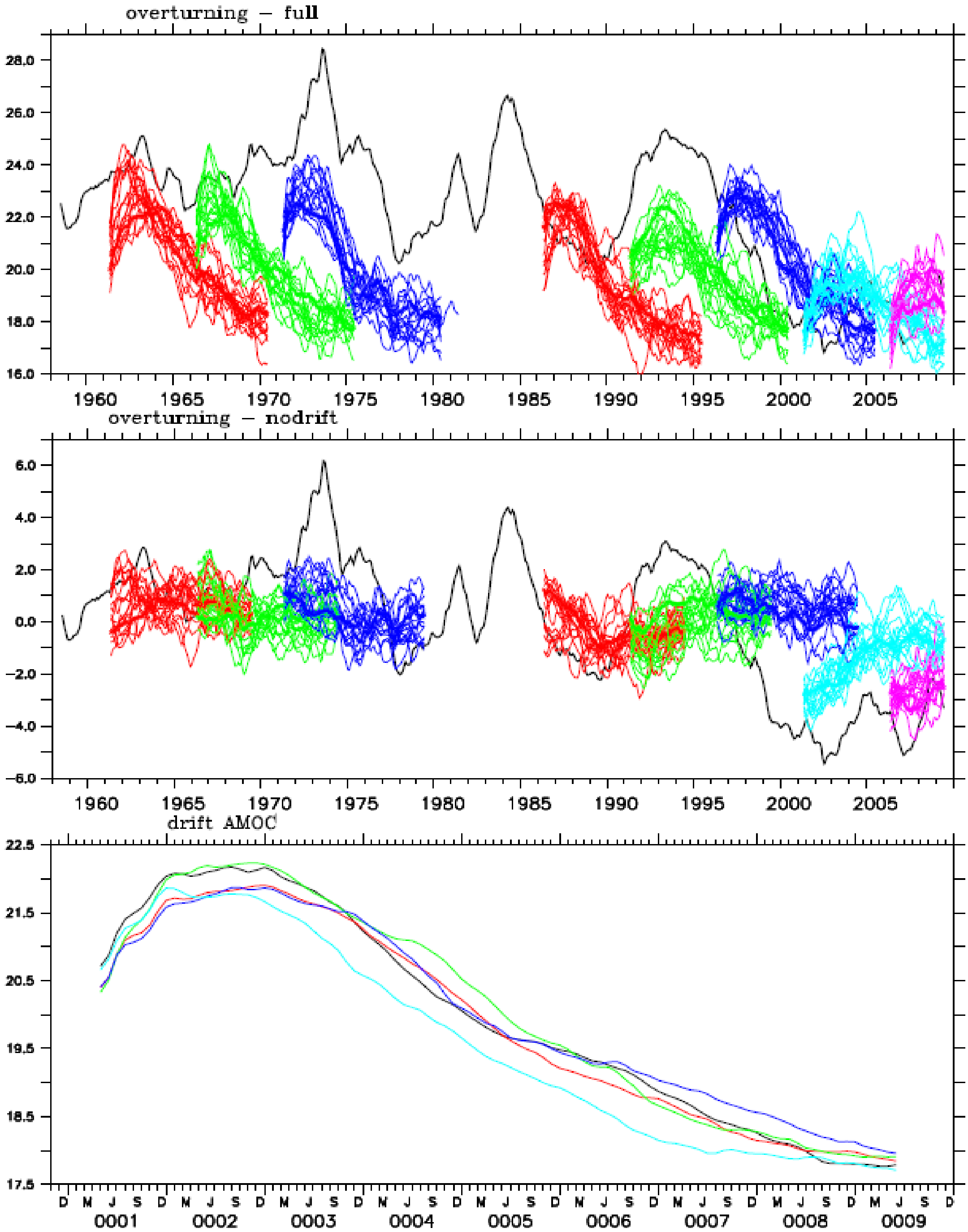

Figure 3.2.4: AMOC strength (in Sv), 12mrm-smoothed. Upper panel: full strength; thick black line: ORAS4, thin coloured lines: 15 individual ensemble members, thick coloured lines: ensemble averages. That the experimental lines do not start at (or close to) the ORAS4 lines is an artifact of the applied 12mrm smoothing. Middle panel: anomalies for ORAS4, drift-subtracted for experiments. Lower Panel: The drift as a function of lead time for five ensembles.

All experiments have been performed with EC-Earth v2.3 (Hazeleger *et al.* 2012, Sterl *et al.* 2012), using full-field initialization. Restart files were chosen from the decadal prediction runs of Wouters *et al.* (2013) and from the ORAS4 ocean reanalysis (Balmaseda *et al.* 2013). For each of the eight start dates three ocean restart files were combined with five atmosphere files. We refer to runs with the same ocean restart file as an ensemble. To test the impact of initialization in different parts of the ocean, experimental ensembles were run in which the initial conditions were changed in parts of the ocean. Results from these ensembles are shown here, too. They exhibit hardly any impact.

After initialization the model starts to drift to its own climatology. The common drift is determined by averaging the model output over all ensemble members and start dates. In the North Atlantic the model drift is very large and dominates the evolution of the ocean state and the large-scale circulation. To show this, Figure 3.2.4 displays the evolution of the strength of the Atlantic Meridional Overturning Circulation (AMOC), measured by the maximum of the Atlantic overturning stream function between 20°N and 50°N. Model values are compared with values derived from ORAS4.

The upper panel of Figure 3.2.4 shows the time-evolution of the AMOC strength. In the experiments (thin colored lines) it is dominated by a common drift and has hardly any resemblance with the ORAS4-values (thick black line). The drift-corrected curves (middle panel) show that the experiments do not contain a useful signal, and the different ensembles cannot be distinguished.

The drift itself is shown in the lower panel of Figure 3.2.4. After increasing by more than 1 Sv during the first two years, the AMOC strength declines by 5 Sv, from ≈ 22 Sv to ≈ 17 Sv. The latter value is close to the climatological value of ≈ 16.5 Sv of EC-Earth (Sterl et al., 2012). To put the magnitude of the drift into perspective it should be compared to the reduction of 2.7 ± 2.3 Sv between 2004-2008 and 2008-2012 as observed by the RAPID/MOCHA array (Smeed et al., 2014), or the ≈ 8 Sv reduction between 1995 and 2003 than can be inferred from Figure 1 for ORAS4. The initial model drift is large, but within observational constraints. The model variability after drift subtraction is much smaller. The AMOC strength varies only by about 2 Sv (Figure 1, middle), which is the climatological range over which the AMOC strength varies in EC-Earth (Sterl et al., 2012). So while the magnitude of the drift is compatible with observed AMOC variations, it by far exceeds the model’s internal variability.

The drift in MOC strength is accompanied by other large scale changes. The strength of the subpolar gyre (SPG), measured as the maximum of the barotropic stream function in a box over the Labrador Sea (LS), decreases by about 10 Sv, and after drift-subtraction no signal remains. The remaining variability is far below that of ORAS4. Convective activity moves from the LS into a region south of Greenland, and it increases in the NE-Atlantic (west of Scotland).This is mirrored by changes in mixed-layer depth (MLD) and temperature and salinity fields, which are all close to the model climate at the end of the prediction runs. The sea surface salinity (SSS) starts to decline immediately in the LS, and after three years also in the central North Atlantic (near 40°W, 45°N). Areas of SSS decrease (increase) coincide with areas of MLD deepening (shoaling), as surface freshening (salinification) inhibits (favours) deep convection.

At depth the drift of the T and S fields occurs highly coherent between ensemble members, but at the surface the fields already start to diverge in the first year. Correlation between members recovers in the second winter, when convection brings water up from lower layers that have not been affected by weather noise during the first year. The basic idea of decadal prediction is that the large heat capacity of the ocean provides a memory which systematically influences the atmosphere for several years. The ocean communicates with the atmosphere via its surface, especially the surface heat flux, which is related to SST. Thus it is no surprise that the fast decorrelation of the SST signal between members is reflected in the heat flux. Figure 3.2.5 shows the heat flux averaged over the SPG. There is a large spread between ensemble members, and large changes in heat flux occur during winter, when deep convection is randomly distributed between members. Subtracting the common drift does not reduce the large variations between ensemble members (Figure 3.2.5, middle). The common drift of the surface heat flux averaged over the SPG (Figure 3.2.5, lower) consists of a drop of nearly 10 W/m^2 within two years. The drop is due to the cessation of the deep convection in the LS: less heat is extracted from the ocean and transferred to the atmosphere during winter.

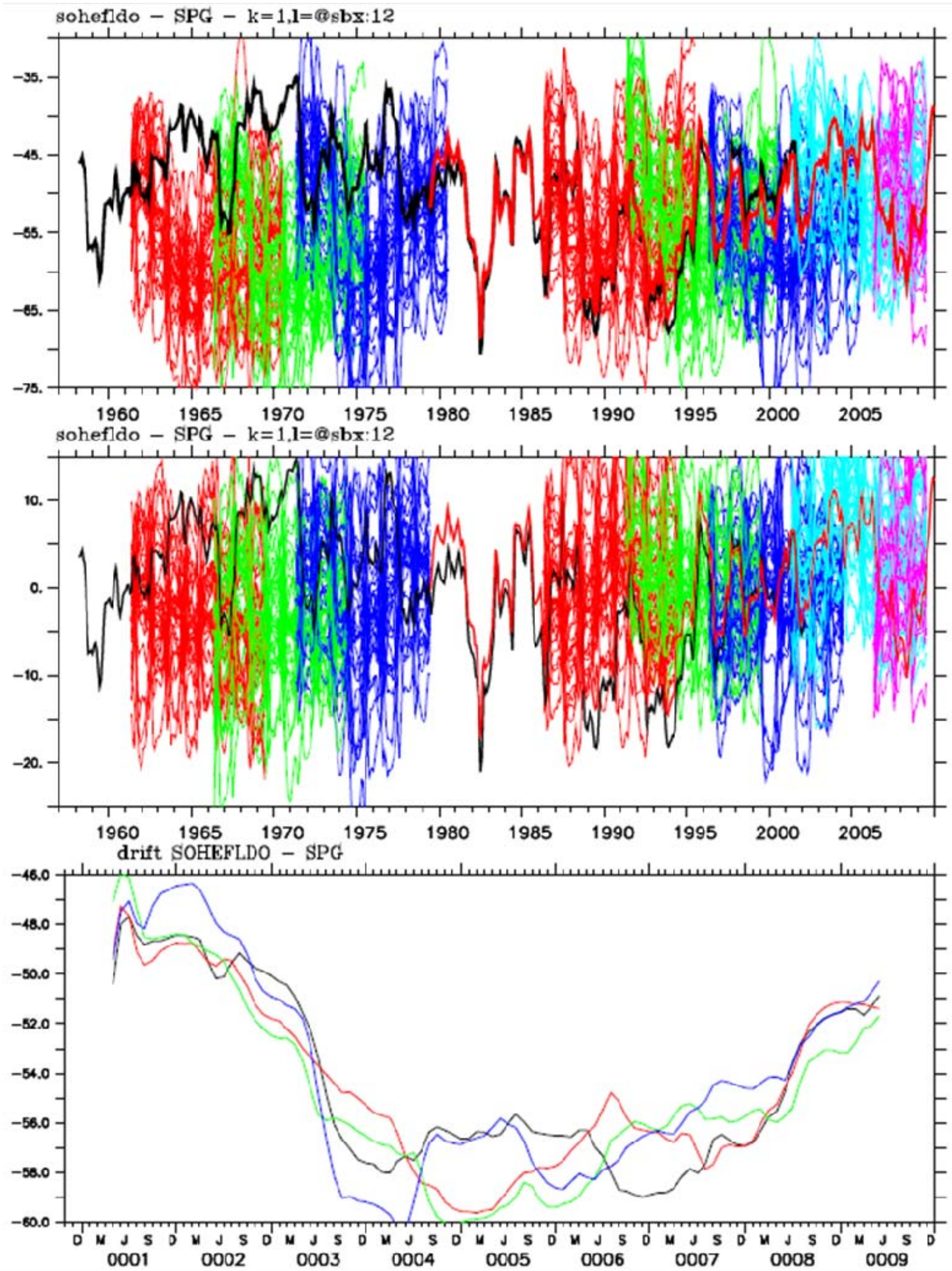

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Figure 3.2.5: Surface heat flux (W/m^2) averaged over the SPG, 12mrm-smoothed. The thick black line is for ERA-40, the thick red line for ERA-Interim. The thin lines are for different ensemble members. Upper panel: Full signal. For the two reanalyses a constant offset of 20 W/m^2 had to be applied to bring the values into the same range as the model output. Middle panel: Anomalies for ERA-40 and ERA-interim, drift-corrected for model. Lower panel: Drift of the surface heat flux as a function of lead time. The different lines are for four different ensembles.

Assuming that cold air from the North American continent needs one day to cross the area of the SPG, the drift-related heat flux reduction of 10 W/m^2 (figure 3.2.5) is enough to reduce the heating of a 1 km column of air by slightly more than 1 K. Due to the westerly flow over the North Atlantic this signal should be advected to Europe and lead to cooling there. Europe indeed experiences a cooling (figure 3.2.6). However, the cooling is strongest in southern Europe and northern Africa and therefore probably not caused by advection from the SPG. Furthermore, it occurs in the first two years, i.e., before the heat flux reduction (figure 3.2.5). It seems that the drift in the atmosphere is not caused by the drift in the ocean, but occurs as an autonomous process. Given the timing of the drifts in ocean and atmosphere the cause-effect relation may be the other way around: The initial fast drift in the atmosphere causes the drift in the ocean which has a longer duration due to the slower oceanic time scales.

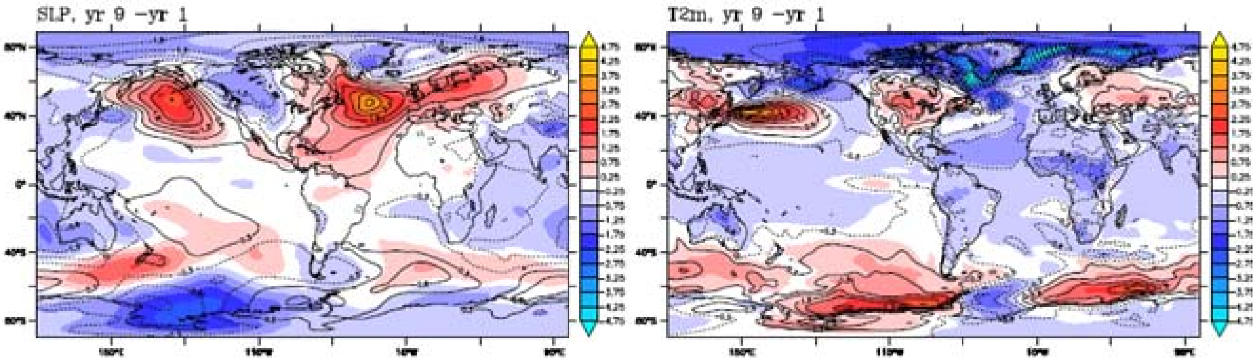

Figure3.2.6: Ensemble-mean differences between year 9 and year 1 for SLP (left, in hPa) and T2m (right, in K) for two different ensembles, distinguished by colours and contours, respectively.

Summary

We have performed decadal predictions runs using EC-Earth with full-field initialization. As these observation-based fields are not compatible with the model climatology, the model starts to drift away from the initial condition towards its own climatology. After subtraction of the drift, no useful signal is left. In the ocean the drift signal is much larger than the model's internal variability, and the drift is discernible over several years. In contrast, the drift in the atmosphere is small and of short duration. It is obviously not caused by the large drift in the ocean. These results cast doubts on the feasibility of decadal predictions, as the assumed mechanism (the large oceanic heat content that systematically influences the atmosphere) is not working, at least not in EC-Earth. However, reported predictability is also low in other models (e.g., Oldenborgh et al. 2012; Hazeleger et al. 2013; Karspeck et al. 2015).

Task 3.3: Mediterranean & Black Sea (Task leader: INGV)

Mediterranean Sea - (INGV)

During the last two years INGV carried out an investigation aimed at the understanding of the impact of the present MedARGO horizontal sampling and vertical/time sampling scheme on the quality of MyOcean Monitoring and Forecasting Center (MFC) operational analyses through Observing System Simulation Experiments (OSSE) and Observing System Simulations (OSE). The simulation results were made available also to the biochemical OSE experiments carried out by OGS.

For the study year 2012, 5 OSE have been carried out in order to study the impact of ARGO data assimilation impact and in general the observational system on the quality of operational MyOcean Med-MFC analyses (Table 1). The basic idea is to remove selectively observations from the overall observing system and assess the impact in term of MISFIT Root Mean Square Errors (RMSE) and BIAS. Misfit is defined here as the difference between the model background and the observation before the observation is assimilated.

Name	Model and Assimilation characteristics	Satellite SLA and SST	In-situ obs	
			XBT	ARGO T,S
CNTRL	Myocean Med-MFC analysis system 2012	✓	✓	✓
OBS-1	MyOcean Med-MFC analysis system 2012 without ARGO data assimilation	✓	✓	
OBS-2	Myocean Med-MFC analysis system 2012 without SLA+SST assimilation		✓	✓
SIM	Simulation (MyOcean Med-MFC model)			
OBS-4	Myocean analysis system 2012 with HALF ARGO	✓	✓	Half

Table 1: OSE characteristics

Results indicate that: 1) Argo assimilation improves the accuracy of the Temperature and Salinity analyses by 35% with respect to simulation on the whole water column; 2) half of the present Argo array increases the analysis bias of 30% for salinity between 0-100 m and 10% in terms of RMSE (7% for T and 12% for S).

The OSSE methodology used here is based on the identical twin experiment approach, which uses synthetic data extracted from a 'Nature run' and the inserted in a 'perturbed run' (Table 2).

Name	Model and Assimilation characteristics	Assimilated data set: synthetic Argo

SIM-TRUTH	Simulation (MyOcean Med-MFC model) for 2012	NO
SIM-PERT	Simulation (MyOcean Med-MFC model) for 2012, perturbed physics and initial conditions	NO
OSSE-1	SIM-PERT with 3Dvar	5 days drift, parking depth 350
OSSE-2	SIM-PERT with 3Dvar	5 days drift, parking depth 700
OSSE-3	SIM-PERT with 3Dvar	5 days drift, parking depth 150
OSSE-4	SIM-PERT with 3Dvar	3 days drift, parking depth 350
OSSE-5	SIM-PERT with 3Dvar	3 days drift, parking depth 700
OSSE-6	SIM-PERT with 3Dvar	5 days drift, parking depth 350, “perfect” vertical sampling

Table 2: OSSE characteristics

Vertical profiles of RMSE (figure 3.3.1) show an improvement when the simulated float drifted with a parking depth of 700m and when probes had a surfacing time of 3 days. Positive impact of perfect sampling has been evaluated to reduce the RMSE error of misfit around the 10-15% in the entire water column.

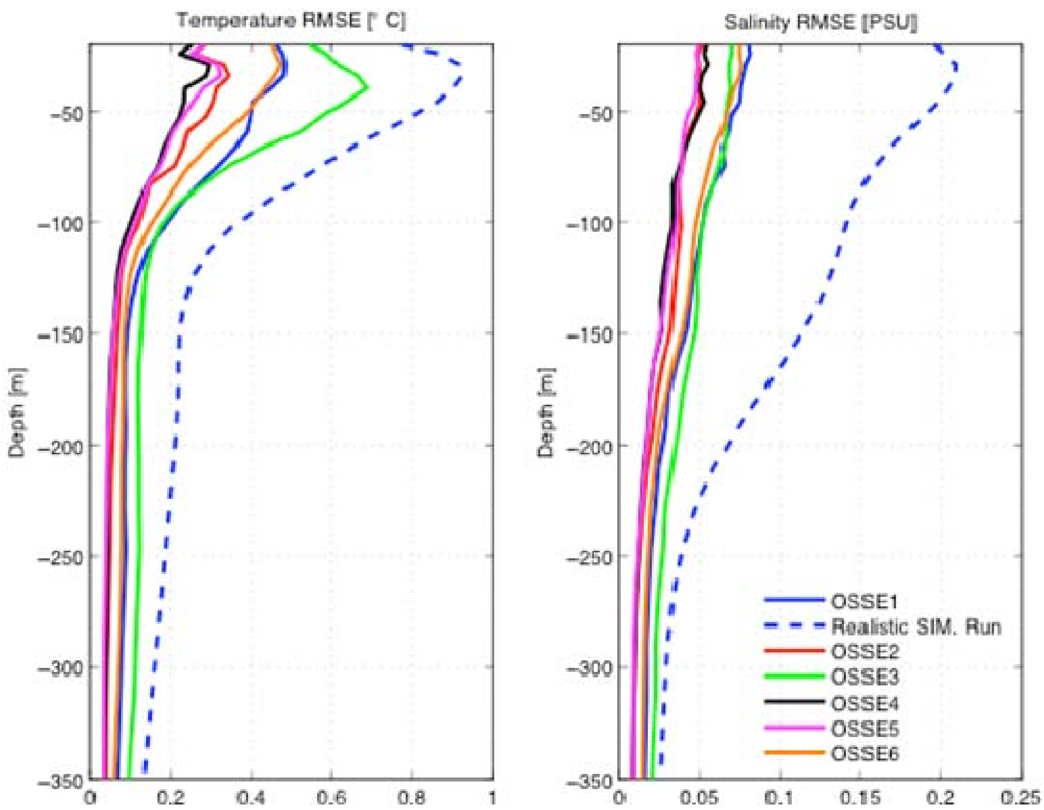

Figure 3.3.1: OSSE Root Mean Square Error (RMSE) for Temperature (left) and Salinity (right)

The OSSE study has shown that the assimilation of temperature and salinity data from synthetic Argo monitoring system in the Mediterranean Sea can improve the quality of analyses if a deeper drifting depth and a shorter drifting time is considered in future Argo sampling schemes. Full profile transmission could be considered also as a major improvement for MyOcean operational analyses.

Black Sea - (USOF)

An observing system in the Black Sea combining remote sensing data such as sea level anomalies from altimetry, sea surface temperature from satellite radiometer and data from Argo floats has been analyzed by the USOF with the aim to quantify the contribution of different information sources when reconstructing the ocean state. The investigated period is 2005-2012. The basic questions addressed during this project-phase can be formulated as follows:

- ✓ do the Argo float measurements substantially impact the quality of estimates of thermohaline fields in the Black Sea;
- ✓ what is the dependence of this quality upon the amount of used profiles and different sampling strategies;
- ✓ what are the specific aspects which have to be considered for the Black Sea when planning future Argo deployments.

Of particular importance for the Black Sea, where the circulation is largely dependent on horizontal and vertical salinity gradients, is that there is no alternative to Argo data, which can be used operationally.

The OSE experiments designed to quantify the quality of temperature and salinity reconstruction as a function of the amount of deep data support the overall understanding that the dynamic information from the deep observations does not strongly propagate onto the whole state vector. However without using deep profiles one cannot well account for the spatial structures of temperature to the east of Bosporus Straits where, if deep-ocean intrusions are not well sampled, the errors increase.

The benefit of using the OSSE as a tool to estimate what impact a new observing system may have on ocean forecasts and analysis and how to maximize the information content of the data collected by observing networks has also been demonstrated. For this type of experiments synthetic observations provided by the model (including synthetic Argo float trajectories) have been used. The accuracy of the pressure sensor which is important for the better resolution of the extremely sharp stratification in the upper layers appeared as one important issue specific to the Black Sea. Increasing this accuracy would have a very high potential to further increase the reconstruction quality.

Experiments with different deployment strategies demonstrated that increasing the amount of Argo floats performs better than increasing the frequency of surfacing. Without Argo data the estimates in the upper mixed layer suffer from large errors. However profiling float measurements are especially important for depth below the seasonal thermocline because the transition from thermo-to-haline-dominated stratification shows only short spatial covariance length.

One major conclusion from this research is that the present abundance 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.

The experiments presented in this work depicted a remarkable sensitivity of the performance of observing network to seasonal changes. The resulting variations in the relative reconstruction errors appeared equal or even greater than the variations due to the enhanced network configuration. Therefore there is a further potential for improving the observation network performance by temporal adaption of its configuration.

Task 3.4: Synthesis (Task leader: Mercator Ocean and CLS)

A workshop was organized to summarize and discuss the main results. The aim of the workshop was to collect evidence of Argo data utility for Copernicus/GMES Marine Service and seasonal/decadal climate forecasting. The impact of Argo observations on the quality of ocean analyses and forecasts was discussed. Based on inputs from this user community, recommendations for long term evolution of the Argo array were presented. This workshop was organized in December 2014 in Toulouse in cooperation with the international GODAE OceanView OSEVal Task Team so that results from European partners were shared with international partners.

From the analysis of results from all partners and workshop discussion, robust recommendations for the evolution of Argo were derived based on an improved understanding of impact and utility of

Argo for GMES Marine Service and seasonal/decadal forecasting and were summarized in the final report.

The OSE experiments show that a sparser spatial coverage of the Argo array than the present one will lead to a degradation of the ocean analysis and forecasts. The Argo floats are crucial to control the water properties, especially at depth up to 2000m. They are necessary to complement satellite observations (SST, SLA) in order to constrain the full 3D ocean state analysis. Below 2000m meter the lack of observation do not allow to estimate the quality of our analysis. On atmospheric analysis with coupled models a clear impact is seen on SST, a little sensitivity of the atmosphere in coupled models to ocean initial/boundary conditions is found.

Results from the present work lead to the following recommendations:

- The existing Argo observing system should be as much as possible stabilized with at least the existing spatial and temporal coverage.

- Deep measurements, sustained and covering the global ocean are crucial for model initialization and validation. The oceans, deeper than 2000 m are mainly unobserved as climate signal are important to accurately estimate and monitor at those depths.

- A higher resolution close to the surface to resolve the diurnal cycle can be beneficial in some regions. In the Black sea, a higher precision pressure sensor for extremely sharp stratification will be useful.

- For some monitoring and forecasting centers, Argo data have to be available with minimal delay, less than a day, from observation time to be used by data assimilative system.

WP4 Impact for the validation of satellite observations and for joint in-situ/satellite analyses

(WP leader: partner 15, CSIC, Spain)

The activities in this WP have aimed to better understand the robustness of the remote sensing validation when Argo data are used. The studies performed during this WP have focused to provide a set of suggestions about the evolution of the Argo array to improve remote sensing validation. The fields under consideration are: Sea level (Task 4.1), ocean colour (Task 4.2), sea surface temperature (Task 4.3), and sea surface salinity (Task 4.4). The total duration of this WP has been 24 months (starting on month one). Each task has provided a set of three deliverables, two of which were delivered during the first year period and the last one delivered during the second year.

The first set of deliverables reported the list of initial requirements that the Argo array should verify to ensure the proper validation for each variable. The second set reported the bibliographic research about past and current efforts to use data from automatic profiling buoys to validate remotely sensed ocean surface parameters. Finally, the last set of deliverables provided a summary of the various impact studies performed and a set of recommendations and a final synthesis. The results were discussed in the WP3 and WP4 Final Workshop held at the CLS premises in Toulouse on December 12, 2014.

Task 4.1 Altimetry (Task leader: CLS)

The deliverable D4.413 (Altimetry: impact study results and Recommendations) describes the sensitivity analysis assessing the impact of changes in the processing of Argo in-situ data in the validation of altimeter measurements for both the global ocean and the Mediterranean Sea (regional study, undertaken by CSIC). The first results of this study have been presented in the E-AIMS WP3 & WP4 final Workshop held in Toulouse on December 12, 2014.

In this study, in-situ steric Dynamic Height is computed by the integration of the Argo Temperature and Salinity vertical profiles. The calculation requires a reference depth. The associated steric Dynamic Height Anomaly (DHA) is calculated by removing a climatology field. The following selection rules are applied to the Argo profiles:

- JULD_QC = 0 | 1 | 5 | 8
- POSITION_QC = 0 | 1 | 5 | 8
- DATA_MODE = 'R' is used and if DATA_MODE = 'A' | 'D', the "adjusted" DHA are used.
- TEMP_QC; PSAL_QC; PRES_QC = 1 | 2. This criteria is only applied for the regional analysis.

Sea level measurements are available along the track of single altimeter missions (e.g. Envisat, Jason-1 & 2, SARAL AltiKa) and as gridded merged products (SSALTO/DUACS products:

http://www.aviso.altimetry.fr/, this including a specific product for the Mediterranean Sea, or ESA/SL-CCI products: http://www.esa-sealevel-cci.org).

The comparison of altimeter measurements with the Argo-derived in-situ steric heights allows the detection of altimeter drift or anomalies at global and regional scales and the assessment of new altimeter standards or products. The present studies have focused on:

- ✓ Sensitivity to the spatial sampling of the Argo floats and the coverage by the network. The altimeter drift detection and the global statistics between both types of data are not affected by a reduction of the number of Argo floats and a reduced spatial coverage of the in-situ network. In contrast, in the Mediterranean Sea there is a larger sensitivity related to the coverage of the Argo network: better scores are obtained when shallow floats are not included in the computation. Furthermore, the sub-basin study shows improved statistics for the western sub-basin for DHA referred to 400 dbar while minimum values are obtained for the eastern sub-basin when computing DHA referred to 900 dbar.

- ✓ Sensitivity to the temporal sampling of the Argo profiles. The Argo floats provide T/S vertical profiles every ten days. A reduced temporal sampling of the floats (>10 days) can prevent us from detecting the impact of new altimeter standards in some specific situations.

- ✓ Sensitivity to the reference depth for the integration of the Argo dynamic heights. The choice of the Reference Depth of Argo profiles impacts the number of valid profiles used to compute DHA and therefore the spatial coverage by the network at global and regional levels, the physical content (variance – see figure 4.1.1) of the sampled water column and the analysis of the altimeter sea level closure budget. Detection of the altimeter drift and the quality assessment of new altimeter standards or products are sensitive to the Reference Depth. A balance has to be found between the vertical sampling of the ocean and the spatial coverage (horizontal sampling) and the choice of the Reference Depth may vary according to the case of study. In the Mediterranean Sea results show that the impact of the reference level in the computation of DH is not statistically significant. However, we recommend that the vertical extension of the Argo profiles should be extended to deeper levels.

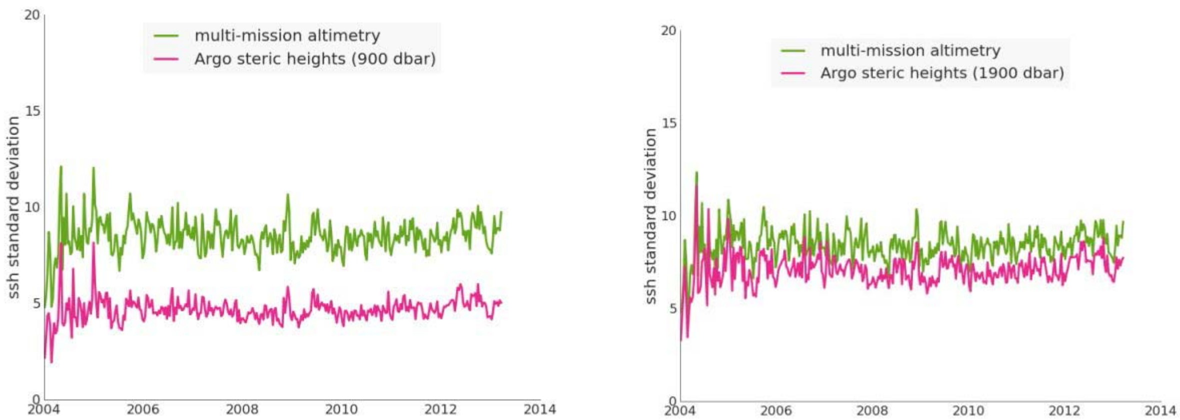

Figure 4.1.1: Standard deviation of the altimeter SLA (green) and the in-situ dynamic heights from Argo profiles with a 900 dbar reference (left) and 1900 dbar reference (right) in the Antarctic Circumpolar Current.

- ✓ Sensitivity to the regions of high ocean variability: The observations in these regions significantly contribute to the global statistics computed between altimetry and Argo data.

However, the results do not allow us to determine whether an increased sampling of these regions by the Argo network would improve the results of altimetry validation.

Additional recommendations can be mentioned:

- ✓ The network coverage should be enlarged at high latitudes, in the Mediterranean Sea and over shallow waters

Task 4.2 Ocean Colour (Task leader: ACRI-ST)

Document D4.422 reviewed past studies and plan for E-AIMS. It also went further into the elaboration of techniques to derive cross-validation of bioprofilers and Ocean Colour.

It appeared Bio-Argo may have a significant impact on ocean colour remote sensing verification and validation. As seen on the figure 4.2.1 below, matchups between Chl-A from remote sensing and Chl-A integrated over the upper layer measured by Bio-Argo are very good and will be improved with new adjustments during the next period.

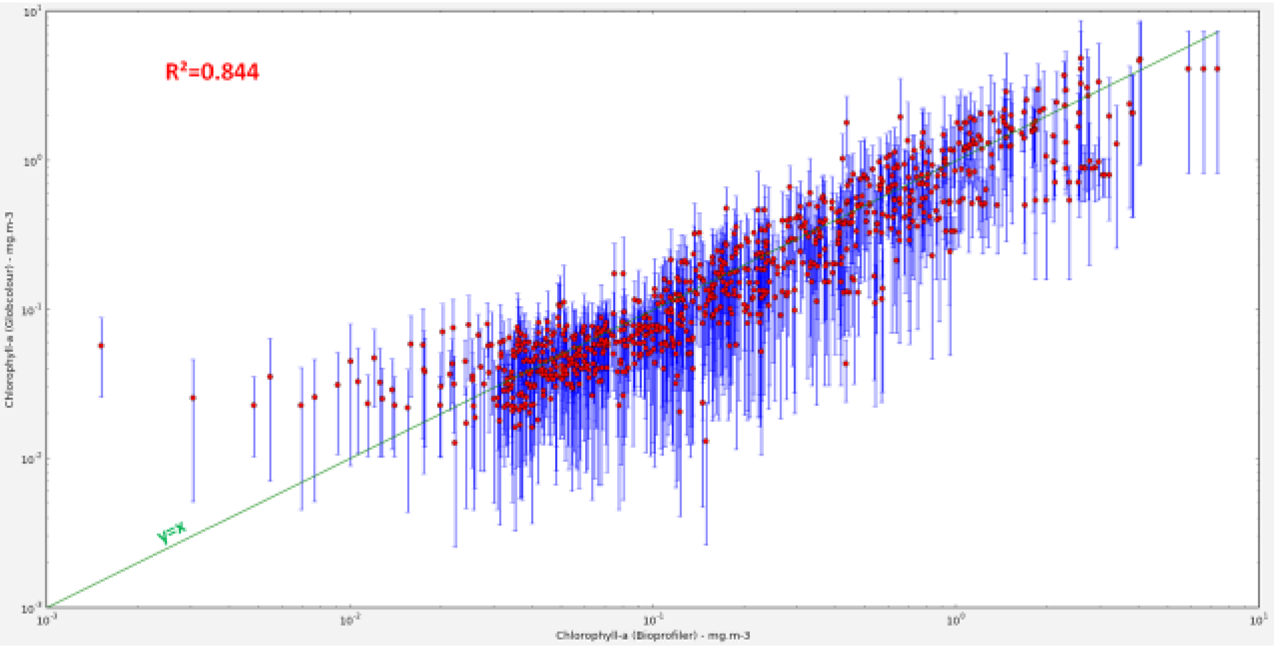

Figure 4.2.1: 875 matchups between Bio-Argo and remote sensing Chl-A (Globcolour)

Indeed, thanks to an increasing number of floats and to the quality of their measurements, the possibility to use Bio-Argo profilers to validate/verify remote sensing data seems realistic. Programing the float to perform its profiling process at the same time the satellite is passing over it could be one of the proposed recommendations to improve the reliability.

Nevertheless, remote sensing only offers a 2D perspective of the studied biochemical variables as the in-depth information is not available. A combination of remote sensing with biogeochemical models (such as the ones used for GMES/Copernicus marine service) already focuses a lot of attention but Bio-Argo could be a very valuable additional input of this kind of assimilation. A constant adjustment between a wide network of in-situ data, model and remote sensing would increase both the amount of trusty data and the consistency. Such merged data will compose a strong tool for assessing biochemical status of our oceans.

Task 4.3 Sea Surface Temperature (Task leader: UKMO)

The work carried out for this task comprises:

- An assessment of sampling requirements for the use of Argo to validate SST in daily situ/satellite analyses
- The implementation of the first routine assessment of OSTIA and GMPE SST products using near-surface Argo data as a reference
- Validation of the new OSTIA diurnal product using high vertical resolution Argo data

The sampling error associated with the monthly mean difference between the OSTIA analysis and near-surface Argo observations (using the shallowest observations between 3-5 m depth) has been investigated. Figure 4.3.1 demonstrates that the monthly total number of near-surface Argo observations is suitable for a sampling error of <0.03 K for most major ocean regions, for the representative example month of December 2013. The exceptions are western boundary current regions, with sampling errors up to 0.082 K, and the Polar regions, with sampling errors up to 0.200 K. Higher sampling errors in western boundary current regions are due to larger standard deviations of Argo-analysis differences in these areas, whereas the higher sampling errors in Polar regions are due to a lack of Argo observations of the ocean under sea ice. The sampling errors in these regions can be a high proportion of the Argo-analysis mean difference statistics. In order to achieve a sampling error of 0.02 K across the global ocean, the number of Argo observations in the western boundary current regions would need to be increased by up to 1300 observations per month (figure 4.3.2).

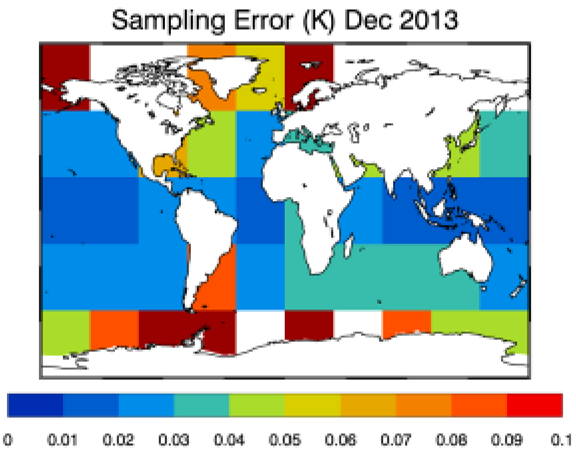

Figure 4.3.1: Monthly sampling error for recent distribution of Argo observations (from SST: Results and Recommendations, Figure 3)

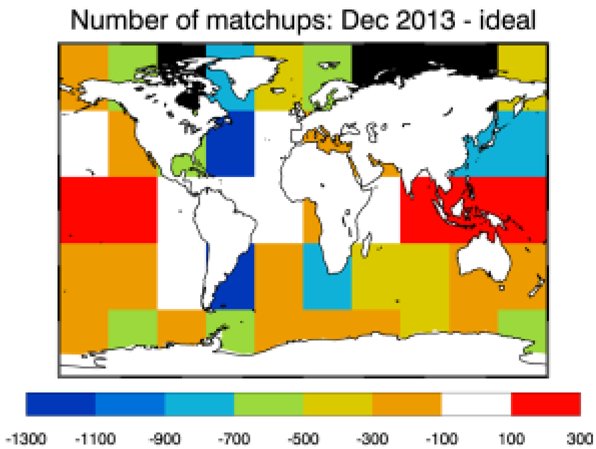

Figure 4.3.2: Total number of Argo near-surface observations for December 2013 minus monthly number of observations required to achieve sampling error of 0.02 K in all ocean areas (from SST: Results and Recommendations, Figure 4)

The largest increase in the number of observations per month would be required in the region of the Falklands/Malvinas current off the coast of Argentina. This region has a similar standard deviation to that of the Gulf Stream, but fewer observations means the sampling error is correspondingly higher (at 0.082 K compared to 0.042 K for the Gulf Stream region). In order for the sampling error of the Falklands/Malvinas region to match that of the Gulf Stream region (the next highest globally), an increase of ~300 observations per month would be required.

The number of available Argo observations is sufficient that regional standard deviations are not dependent on this number when calculating monthly statistics. The North Atlantic is a possible exception, suggesting more floats are needed in this region. At numbers of observations available for calculation of weekly or daily statistics, standard deviation is dependent on this number and is therefore unreliable. The number of observations needed for convergence towards a reliable standard deviation varies with ocean region, depending on the variability of the region.

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 previously demonstrated. Regions with larger standard deviations require more observations to determine statistical significance of differences between analyses. The Pacific has comfortably enough observations to demonstrate statistical differences between the analyses, whereas the maximum number of observations available in the South Atlantic is only just high enough to produce a consistent "statistically significantly different" result. This demonstrates a requirement for more floats in the South Atlantic.

The results from the assessments of standard deviation reliability and detection of statistically significant differences between analyses illustrate that more floats are needed in the North and South Atlantic respectively. These results were not broken down into smaller regions but it is reasonable to assume that the results are due to the high variability in the Gulf Stream and Falklands/Malvinas regions respectively.

The uncertainty on mean and standard deviation statistics of analysis differences to Argo can be quantified using a bootstrap method. It is recommended that it should become standard to present these statistics with uncertainty estimates, to take into account that some regions will have high sampling errors.

The size of ocean area used to calculate assessment statistics is a trade-off between the ability to identify regional issues and the need to obtain sufficient observations to produce reliable statistics. An increase in the number of near-surface Argo observations available would be required to validate SST analyses on weekly or daily frequencies, or monthly over smaller regions than those defined by MyOcean. The current distribution of Argo floats (nominally 3x3^{o}) should be maintained in order to allow their use for monthly validation of SST analyses over the MyOcean regions to continue.

Routine monthly validation of OSTIA and GMPE SST products using quality-controlled Argo observations from the EN4 database[1] has now been set up. Time series of global and regional statistics (using the MyOcean region definitions) are freely available on the web:

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[1] Good, S. A., Martin, M. J. and Rayner, N. A. (2013), EN4: quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. J. Geophys. Res. 118, 6704-6716, DOI: 10.1002/2013JC009067.

http://ghrsst-pp.metoffice.com/pages/latest_analysis/sst_monitor/argo

Statistics will be updated on a monthly basis. Uncertainty estimates are shown on plots of both mean and standard deviation of the differences between the analyses and Argo, obtained from 95% confidence intervals using a bootstrap method.

High vertical resolution near-surface temperature observations from Argo have also been used to validate the new OSTIA diurnal analysis product. A procedure consisting of pumped-unpumped adjustment, spike check, removal of mixed air/water measurements and diurnal cycle signal test has been established to extract and pre-process the high vertical resolution Argo near-surface temperature profiles. The mean (standard error) of the difference between the OSTIA warm layer SST analysis and the Argo observations in September 2014 in the Atlantic Ocean is 0.23 K (0.16 K). Argo near-surface temperature is warmer than the OSTIA warm layer SST at the surface, which appears to be related to a bias introduced in the pre-processing of assimilated SEVIRI data and requires further investigation.

The currently available floats with high resolution near-surface temperature provided only 11 daytime profiles which passed all tests and were used for the validation of the diurnal analysis in September 2014 in the Atlantic Ocean. More available profiles would certainly improve the robustness of this and future validation. Further improvements to the vertical resolution of the profiles would also be useful for the validation of diurnal SST analyses, as the temperature can vary significantly under a strong diurnal cycle within a small vertical range. 0.1 dbar resolution in the very top 5 dbar would be ideal though the methods to flag potentially bad data would need to be improved.

Task 4.4 Sea Surface Salinity (Task leader: CSIC)

The work done during the second period of twelve months of this task has focused on the actual results of using Argo data to validate the SMOS sea surface salinity (SSS) products. This study has been summarized in the third Deliverable provided by this task (D4.443: Results and Recommendations) and were presented in the E-AIMS WP3 & WP4 final Workshop held in Toulouse on December 12, 2014.

These validation activities have relied on the match-up pairs between the estimate of the SSS provided by the products generated at the SMOS-BEC (http://cp34-bec.cmima.csic.es/) and an estimate of the SSS estimated from an Argo salinity profile.

Three SSS products have been used for the validation activities. All these products are defined on a 0.25 degree grid and correspond to nine-day time averages (every three days). The three products are: i) A binned product (called L3) constructed from the weighted average of all the Level 2 SSS retrievals produced by ESA; ii) An optional interpolation product (called OI) that is used to extrapolate and reduce the noise of the L3 product; and iii) A data-fusion product (called L4) that merges the L3 salinity information with the information from OSTIA sea surface temperature data.

In the case of the Argo profilers, the following selection rules are applied to estimate the SSS value:

- The profile must contain Delayed Mode quality controlled data.
- Only the primary CTD measurements from each profile are used.

- Pressure, Temperature and Salinity must have an associated Quality Control of "good".
- The Quality Control of geographical position and date position is accepted if it has been set to 1 (good), 2 (probably good), 5 (Value changed) or 8 (Interpolated value).
- The salinity value used will be the closest one to the surface (although values shallower than 0.5 m are disregarded).
- Salinity data from PROVOR, SOLO (as well as for those profilers where the profile type variable is set the UNKNOWN) instruments are not considered at depths shallower than 5 m. These profilers did not pump water at a depth shallower than 5 m].

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.

After a series of sensitivity experiments, the following criteria are used to account for a match-up between SMOS and Argo:

- The Argo data must have been taken no deeper than 10 m below the ocean surface.
- The match-up has to be located farther than 1000 km away from the coast.
- The surface temperature estimated from the in-situ Argo must be between 5C and 28C.
- The average precipitation for the corresponding match-up than 1 mm/day.
- The difference between the SST value used during the SSS retrieval and the uppermost measure of temperature obtained by the Argo profile should be smaller than 1C.

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 in the 30S-30N band respectively. A slight negative bias (SMOS fresher) has been systematically found: -0.01 and -0.03, respectively. In the tropical region, the systematic bias becomes even more negative when match-up pairs under the influence of rain are included. On the other hand, studies in which the match-up is restricted to those Argo profiles where salinity measurement is shallower than 4 meters, the sign of the bias changes from negative to positive. The raison of such behavior is still unclear and additional research and information is required.

Finally, a series of experiments have been performed to address the issue of including Real Time data in the validation of SMOS SSS. This has been done by comparing the validation when, in the Delayed Mode profiles, the real time salinity (PSAL) or the adjusted one (PSAL_ADJUSTED) has been used. The mean difference between both is 0.00 and the standard deviation is 0.02, i.e. one order of magnitude smaller than the difference between SMOS and Argo.

Thus, further increase in the understanding of the error sources contaminating the SMOS retrievals and the improvement of the monitoring of the satellite quality would benefit from:

- ✓ Speed up of the scientific calibration (Delayed Mode) process of Argo data.
- ✓ Increase the number of measurements in the upper four meters of the ocean

Task 4.5 Synthesis (Task leader: CSIC)

The E-AIMS WP3 & WP4 Final Workshop was held at CLS, Toulouse on December 12, 2014. It was organized after the international OSE/OSSE workshop organized jointly by the GODAE

OceanView OSE Task Team, GSOP/CLIVAR and E-AIMS. The workshop introduced the final results of the impact studies from the Copernicus Marine Service and from the seasonal/decadal forecasting centers (Mercator Ocean, UKMO, and INGV). It also introduced the final results and recommendations from the validation of remote sensing data (Altimetry, Ocean Colour, Sea Surface Temperature and Sea Surface Salinity).

The results summarized in the Deliverable D4.453 (Final synthesis report) suggest that, although 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), further improvements may help to improve the robustness of the validation of these remote sensed variables:

1. **Speed up of the scientific calibration (Delayed Mode) process of Argo data**. This decline leads to situations where some ocean basins are not properly sampled.
2. **Increase the vertical extension of Argo profiles.** The detection of the altimeter drift and the quality assessment of new altimeter standards or products are improved when deeper reference levels are used.
3. **Increase the number of measurements in the upper four meters of the ocean**. Currently, the spatial coverage of the oceans of the ocean surface is ensured when we consider measurements in the first ten meters of the ocean. However salinity validation considering salinity measurements at depths shallower than 4 m has a statistical behavior different than when surface data are taken deeper than 5 m.
4. **Increase sampling in regions of high variability**. In order to reduce the sampling error in regions of high variability the number of floats would need to be increased. In regions like the Falklands/Malvinas Current about 300 observations per month are found to be required to provide low sampling.
5. **Network coverage should be enlarged in the Atlantic Ocean.** Although the Atlantic Ocean has been one of the most sampled areas of World Ocean, the Argo array provides little coverage compared with its variability, especially in current Delayed Mode data.
6. **Network coverage should be enlarged at high latitudes.**
7. **Network coverage should be enlarged in the Mediterranean Sea.**

As the operational situation of bio-profilers is different than the development of hydrographic floats, several particular requisites are proper to the deployment of bio-profilers:

8. **Optimise the matchup strategy.** For example, program biofloats to maximize the number of matchups with Ocean Colour satellites.
9. **Program high frequency profiling cycles when located in a biological stable area.** Increasing the number of repeated samplings increases the estimate of the precision of the sensor in term of dispersion around a common value.
10. **Make use of additional recoverable profilers at launch and recovery times**. A parallel sampling strategy will help ensuring the initial calibration of the instrument.

WP5 R&D on Euro-Argo data system and interfaces with Copernicus/GMES Marine Service

(WP leader: partner 1, Ifremer, France)

The objective of WP5 was to undertake the R&D activities necessary 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 (biogeochemical, deep, high vertical sampling). It was divided in 3 tasks which were dedicated to:

- The development of Real Time and Delayed mode QC procedure for oxygen variable;
- The development of Real Time and Delayed mode QC procedure for other biogeochemical variables;
- Enhancement of the European Argo DACs (Data Assembly Center) to process the new generation floats tested in WP2.

This work needed to be achieved within the Argo International framework with QC procedures agreed with Bio-Argo partners as well as changes in the data format and processing chains that were necessary for the data management of these extensions to Argo. This was managed within the time frame of the E-AIMS project and Bio-Argo data started flowing to the Argo GDAC (Global Data Assembly Center) in 2015.

Task 5.1: Define, prototype and test real time and delayed mode data processing techniques for oxygen variable (Task leader: Ifremer)

The objective of this task was to reach an international consensus on the real-time and delayed-mode quality control procedures of oxygen data from autonomous profiling instruments. During E-AIMS project the following sub-tasks have been achieved:

The manual describing the management of oxygen data has been delivered to the Argo community (Thierry *et al.*, 2015). This manual provides guidelines on the processing of the oxygen data taking into account the technology developments that happened during the project both in term of oxygen sensors and calibration equations. This manual and complementary documents or programs are available on the Argo data management website: http://www.argodatamgt.org/Documentation/Bio-Argo-Oxygen-data-management-by-DACs. The manual will continue to be updated when needed within the Argo International Data Management group. The new Argo data format designed for handling bio-argo data has been defined. The core parameters (p, T, S) are in the so-called c-file. Oxygen data, as well as other biogeochemical data, are in the so-called b-file (see http://www.argodatamgt.org/Documentation).

Real-time quality control tests for oxygen data were defined and validated by the Argo Data Management Team in 2012 (Wong *et al.*, 2014). They are now implemented in most DAC.

In terms of delayed mode, the existing methods are based on adjustments from climatology, from reference calibrated in situ data and from “in air” measurements (Takeshita et al, 2013, Bittig et al, 2015, Johnson et al, 2015), The first method is useful when in situ or “in air” measurements are not available. Using reference in situ data provides much better results, especially in areas where the climatology is not well defined or subject to large inter-annual variability (e.g., North Atlantic Ocean). The functioning and utility of in-air oxygen measurements as a means of *in situ* calibration and drift correction of oxygen optodes on Argo floats was recently demonstrated by Bittig et al, (2015) (see WP2 results above) and Johnson et al, 2015). Based on those results, the SCOR WG 142 proposed to implement in-air oxygen measurements on all future Argo oxygen floats and provided recommendations on how to achieve those measurements.

The **optimal interpolation tool ISAS** initially developed for temperature and salinity data (Gaillard *et al.*, 2008) was adapted to oxygen data. This tool is useful for a careful secondary quality control procedure and for interpolating data on isobaric levels. A first analysis of all Argo oxygen data available since 2004 and adjusted from the WOA climatology or from a reference calibrated in situ data was done (figure 5.1.1).

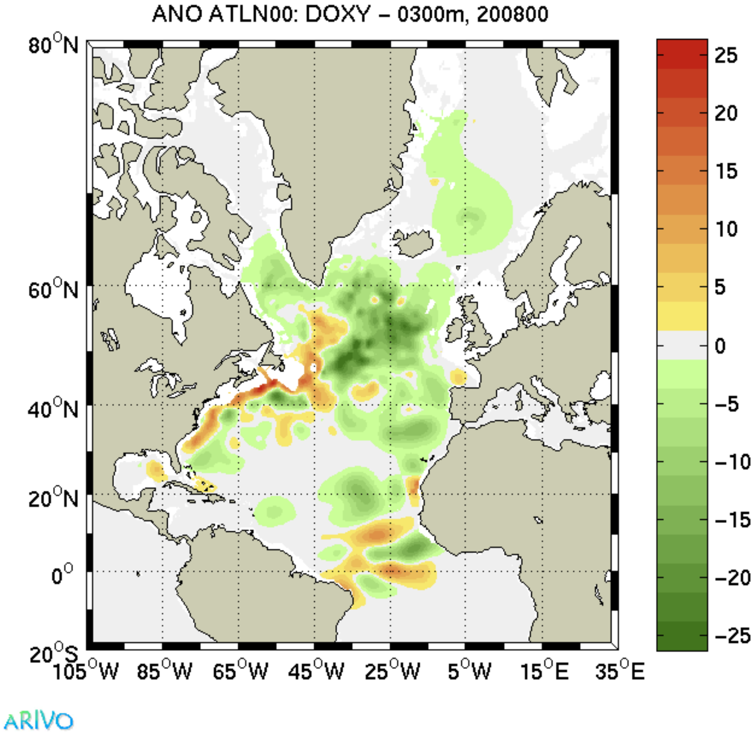

Figure 5.1.1: Dissolved oxygen concentration anomaly at 300 m depth compared to the WOA09. All Argo oxygen data available at Coriolis GDAC were interpolated with ISAS. The real-time and delayed mode QC procedure was applied to the data before the interpolation.

Task 5.2: Define and test real time and delayed mode data processing techniques for other biogeochemical variables (Task leader: ACRI-ST)

The objective of this task was to reach an international consensus on the real-time and delayed-mode quality control procedures of Chl-a but also bbp and nitrates (NO3) data from autonomous profiling instruments. During E-AIMS project the following sub-tasks have been achieved:

- The first goal has been to define and tune QC tests and, once validated, to discuss them within the Bio-Argo Argo Data Management Committee for implementation. Five tests have been, established in partnership with the experts in LOV, following a sequential procedure allowing different flagging score at the end of the process. These procedures have been agreed at international level and transferred to the Operational DAC to be performed automatically. For Chl-a, the tests are mainly addressing: the *dark value* (which is the value of Chlorophyll value at high depth which should be equal to zero), a *range value* out of which the Chlorophyll is considered as non-valid, a *negative spike filtering* and a *correction of quenching*. This last correction is rather sensitive and has been subject of fine tuning as it seemed to be an over-correction when compared to available information from satellite. For this reason, and because quasi all profiles were subject to this quenching problem, it has been decided, later in the project, no to QC-flag the profiles whose Chl-a concentrations have been corrected, but preferably to annotate them with a "interpolation" label. For bbp and nitrates (NO_3), the real time QC mainly consists in a flagging and in an optionally correction if the data is not lying in a predefined range of values. These procedures have been specified and documented and will continue to be updated within Argo International.

- The second goal was to investigate on QC methodology in Delayed Mode in order to develop set of metrics/indicators and technics to assess quality of observations and produce synthesis of these metrics that would facilitate delayed mode QC in particular for Chlorophyll. The methodology proposed is based of intercomparison with other floats operating in the same area, data continuity between successive profiles within a reasonably narrow time/space window have to be correlated.; matchups with coincident ocean colour (Globcolour); and finally comparison with climatology under the form of bio-regions. The climatology has shown to be too complicated to be globally applied and will thus need larger investigations (too many temporal and spatial scale in biochemistry that deserve to be better known and documented before being applied for DM QC activities). All these indicators have been made available through a dedicated web site offering large flexibility to the experts for QC and validation (http://www.seasiderendezvous.eu). An example of expert dashboard is displayed on figure 5.2.1. The relevance of every test and indicators is examined with a statistical approach. According to this analysis, these quality indicators might be slightly adapted in the near future. The float is identified using its WMO code and the PI can download a detailed CSV file reporting the status of all the parameters displayed in the graphics.

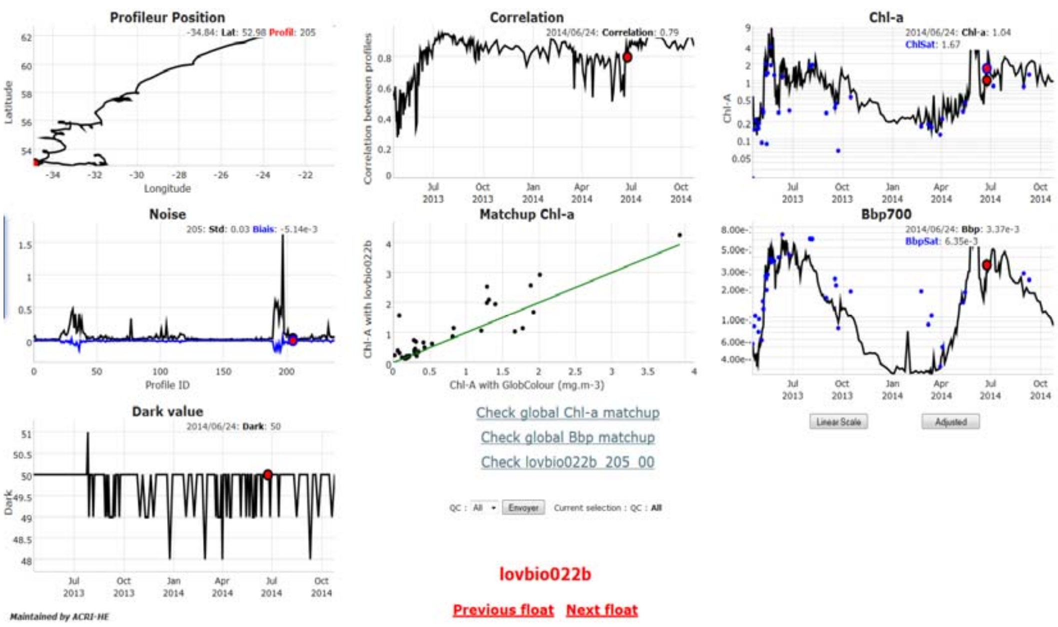

Figure 5.2.1: Example of expert dashboard. The relevance of every test and indicators is examined with a statistical approach.

Task 5.3: Develop the Euro-Argo DACs for the new Argo floats (Task leader: Ifremer)

Within WP2, new types of floats have been deployed that implement new data transmission schemas and required enhancement of the floats format to integrate the new variables and therefore upgrade of the Euro-Argo data centres processing chains. These changes have been tested at Euro-Argo level and discussed with the International Argo Data Management partners at the Argo Data Management meetings held on November each year as it was important to maintain coherency between the European Argo fleet data and the international Argo fleet. Final agreements were reached at the Argo Data Management meeting (ADMT) in Ottawa in November 2014

The two Euro-Argo DACs (Ifremer/Coriolis and BODC) have upgraded their processing chains to process deep floats and high resolution surface profiles coming from multiple float providers (NKE, WEBB, SeaBird, METOCEAN). For Bio-Argo data management, Ifremer/Coriolis and BODC took a leading role in the definition of Bio-Argo data format at the Argo Data Management Meeting that was held in November 2013 in Liverpool and in November 2014 in Ottawa. The implementation of 2013 agreement in Ifremer and BODC processing chains for biogeochemical floats both in Arctic and ice free oceans have been turned into operation and finalized during summer and autumn 2014.

Real time data processing and quality control for Oxygen have been implemented both at BODC and Ifremer/Coriolis and results reported at ADMT meeting in 2014 while. Real Time processing of biogeochemical variables and Real Time Quality control procedures were implemented in 2015 at Ifremer/Coriolis and BODC as final agreement were reached in November 2014 during the International Bio-Argo meeting that was preceding the ADMT in Ottawa. At the end of E-AIMS, the two Euro-Argo DACs are able to process WP2 floats in agreement with Argo International recommendations.

WP6 Real time processing, impact and final assessment

(WP leader: partner 3, OGS, Italy)

Task 6.1: Real time data processing of new Argo floats and interfaces with MyOcean (Task Leader: Ifremer)

The purpose of this task was to process the new floats deployed within E-AIMS using the updated processing chains and quality control procedures set up in WP5.

Both BODC and Ifremer/Coriolis have set up the processing chains to decode the WP2 floats. The processing chains have been turned to operation and the data delivered to the Argo DACs. Since summer 2015 the floats can be delivered to the Argo GDACs that were updated to accept these extensions to Argo. Following the Argo Data Management meetings in Ottawa in November 2014 and Bermuda in November 2015, both Coriolis and BODC are updating their processing chain to take into account the meeting recommendations.

The real time QC procedures for oxygen and chlorophyll developed in the task 5.1 and 5.2 have been turned into operation and applied not only to the E-AIMS floats but to all European flats measuring those parameters.

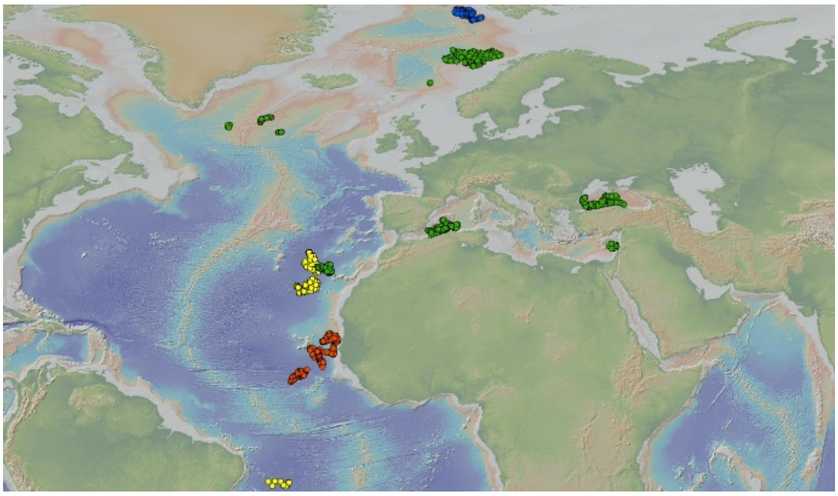

Figure 6.1.1: Map of the E-AIMS floats: APEX (yellow) PROVOR (green) NEMO (red) NAVIS (blue)

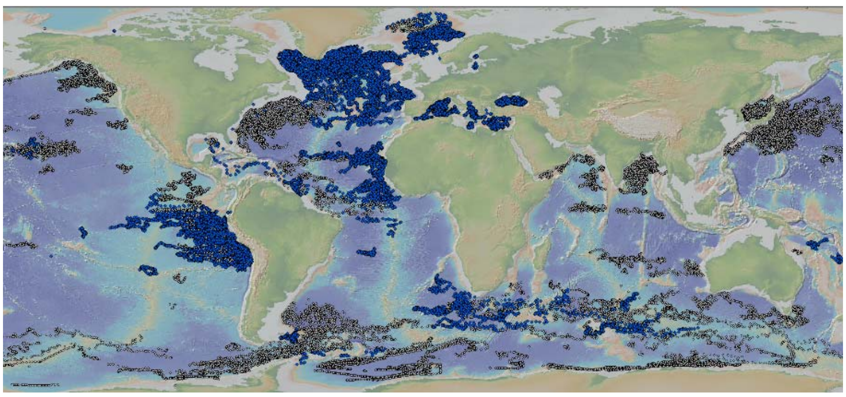

Figure 6.1.2: Map of the 294 bio-Argo floats deployed by E-AIMS and other European projects. Blue dots: EU floats, grey dots: the other bio-Argo floats (USA, Australia, Japan, Canada, India).

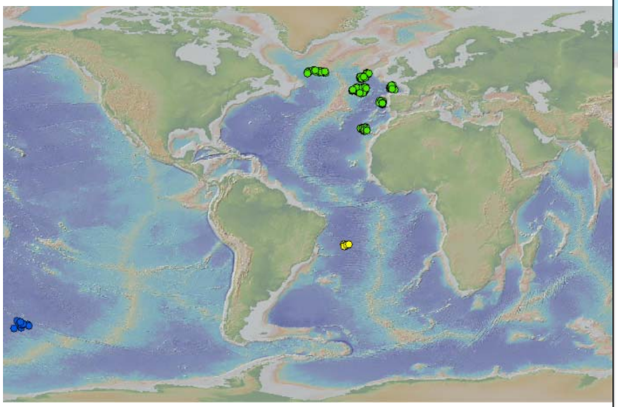

Figure 6.1.3: Deep Argo floats: 6 E-AIMS Euro-Argo floats (green), 1 US float (yellow), 6 Japanese floats (blue)

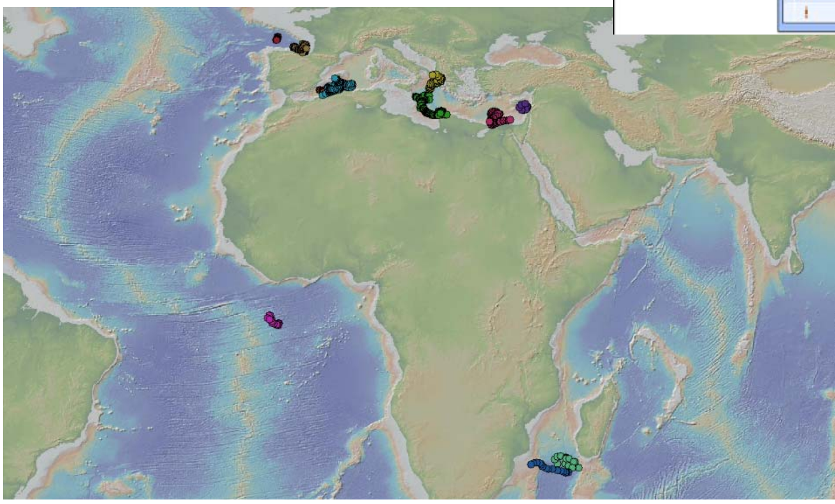

Figure 6.1.4: Argos3 floats: 11 floats equipped with the new Argos3 bi-directional communication

The temperature and salinity measurements are sent to the GTS for distribution to meteorological agencies as well as the near surface temperature and the oxygen as the BUFR format template for Argo has been validated by WMO. For the other bio-Argo parameters it will take longer and is likely to happen after the end of E-AIMS (action at WMO level).

E-AIMS float data are delivered to the Argo GDAC (all parameters) for the Argo community. The Argo data have also been integrated in the Copernicus Marine Service In-situ Thematic Assembly Centre for distribution to the Copernicus Marine Service Monitoring and Forecasting Centres and well as Satellite Thematic Assembly Centres. These data have been used by task 6.2 and task 6.3 for their impact studies.

Figure 6.1.5: Access to E-AIMS float data
http://www.coriolis.eu.org/Data-Products/Maps-corner/Argo-Projects/Europe/E_AIMS

Task 6.2: Impact and use for Copernicus/GMES Marine Service (Task leader: Mercator Ocean)

This task represents an end to end test. It started on the last year of the project when E-AIMS floats were deployed and were shown to produce qualified data distributed by the Coriolis data center (Copernicus Marine In-situ TAC). The different monitoring and forecasting centers within Copernicus used those data for validation and assimilation in real time. The objective was to demonstrate that Euro-Argo data centers can process in real time the new floats developed and tested in WP2 and distribute them to the GMES/Copernicus monitoring and forecasting centers for validation and/or assimilation. The suitability of the data in terms of timeliness, robustness and quality was assessed within the operational context.

This task was an opportunity to revisit the entire chain from instrument measurements down to their use in real time applications.

First an inventory was done on the data base used by the monitoring centers to verify that the observed profiles were distributed and arrived on time for operational applications, with the required quality. Most of the observations were available within a few days. In case of monitoring and forecasting system running with an assimilation window equal or less than two days, like the Met Office system, some of the data were not available for assimilation.

The other use of the in situ profiles is for validation of the production. In this context, time constraint is less restrictive. This could be done in near real time when most of the data are available. Model data comparisons were performed by different monitoring and forecasting centers. Individual and time series of observed and forecasted profiles were produced and compared for physical and biogeochemical variables.

The next figures show temperature and salinity model observation comparison for some of the E-AIMS floats. Examples are chosen in the Mediterranean Sea and in the North East Atlantic to illustrate the comparison studies presented in the report D6.621.

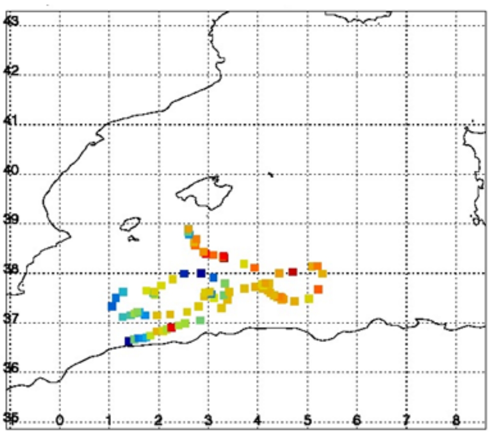

Figure 6.2.1: Trajectory of the float number 6901876 in the Western Mediterranean Sea, colour represents the misfits.

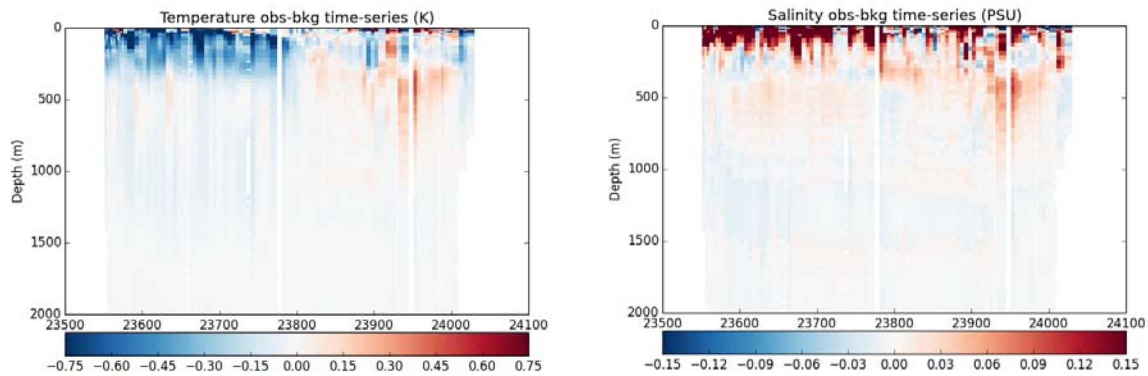

Figure 6.2.2: time-series of temperature and salinity observation-background profiles over the period the float 6901876 was assimilated into the FOAM system.

In the first time period, the misfits are large and are then reduced too much smaller amplitude on the second period. The patterns found by FOAM (shown here) and the Med MFC (not shown) are comparable even if the data assimilation systems differ.

The figure 6.2.3 shows a similar comparison but for a deep float deployed north of the Spanish coast in the Bay of Biscay. As that type of measurement was quite new, Argo requirement was to set the QC to two (suspicious) for deep measurements, this was done in the second time period: deep measurements were then not assimilated. The use of restrictive QC flag prevents bad or suspicious data to be assimilated.

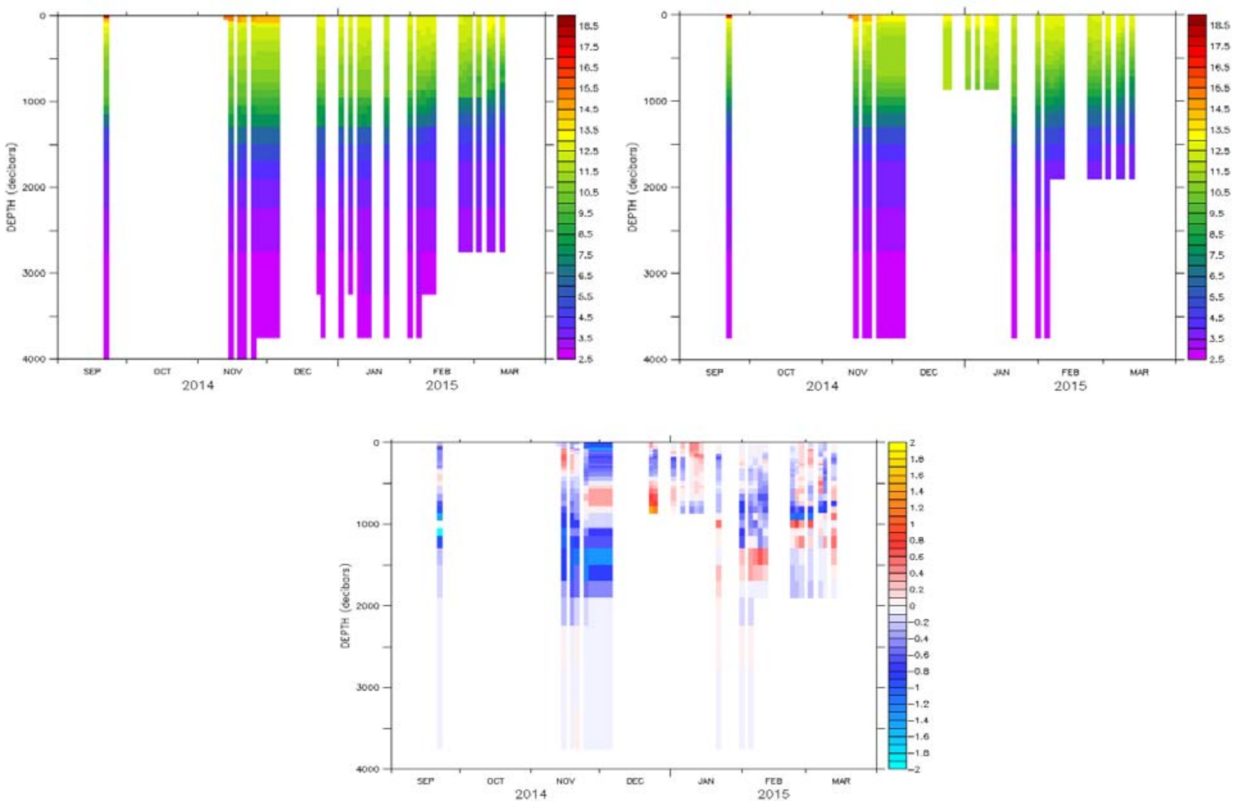

Figure 6.2.3: Time series of the temperature profiles of the float 6901632. Top left: observations, top right: model analysis (Mercator Ocean), bottom: difference between the model and the observations.

Finally, the agreement between the observation and the models greatly vary in time and depends on the region.

The QC flags are one of the key for a beneficial assimilation in ocean model. The assimilation system highly relies on the data selected to be assimilated. Only one float was found to have suspicious profiles when compared to global model outputs: the float number 6902547 west of the Norwegian coast.

The examples presented show the efficiency of the overall system from testing new instruments, launching floats and sending in real time the information so it can be used by GMES/Copernicus Marine service for assimilation and/or validation after a proper QC.

We also illustrated the benefice of high frequency assimilation of profiles in a quickly changing environment such as on the western side of Svalbard, along the continental shelf. Model tends to have difficulties to maintain intermediate water masses at the right depth and with the correct T/S properties. In situ profile assimilation is essential in such situation.

Finally comparison with E-AIMS Bio-Argo floats were also carried out (figure 6.2.4) and they illustrate the high potential of Bio-Argo observations for the validation of Copernicus Marine Service biogeochemistry models.

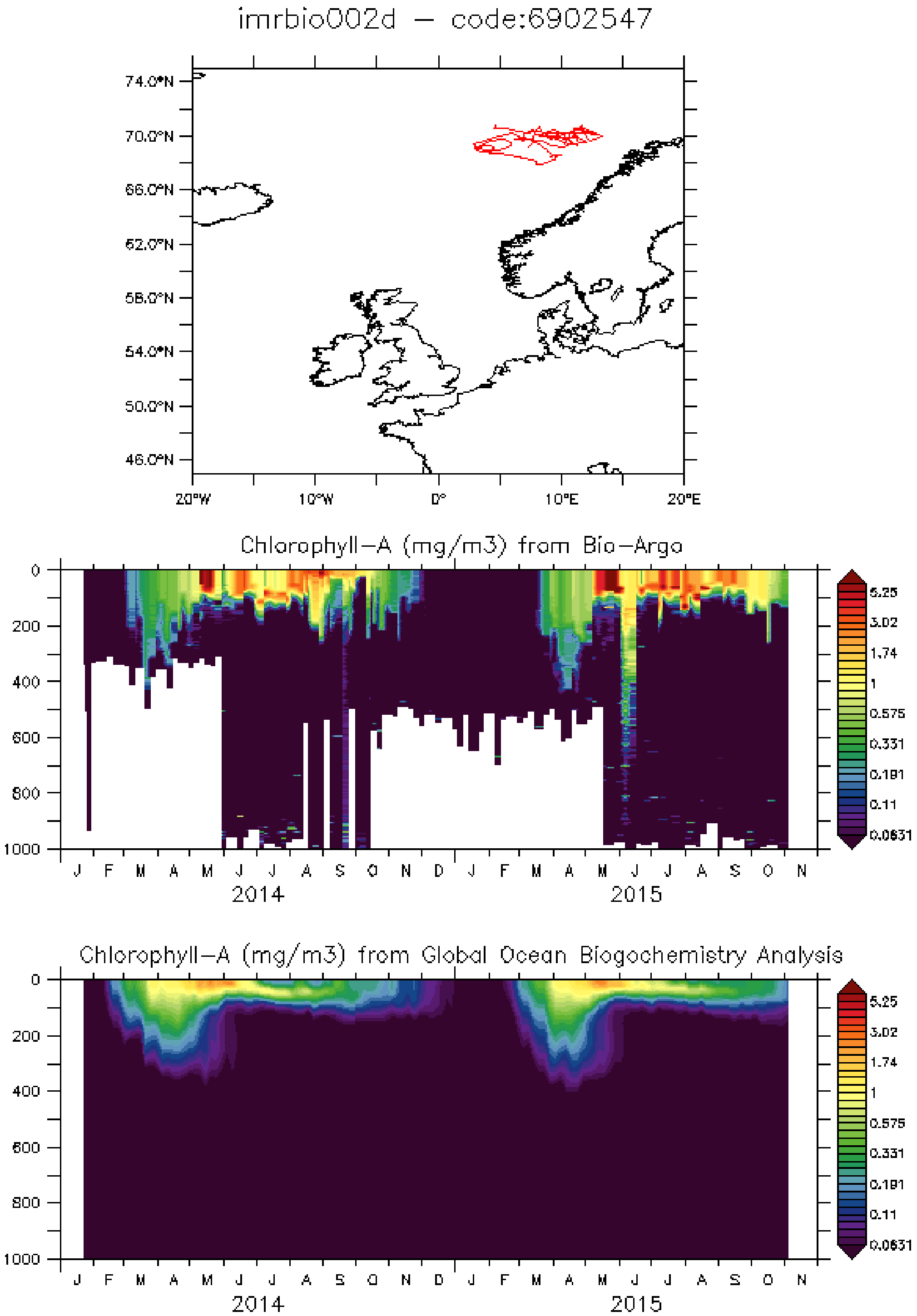

Figure 6.2.4: Comparison of Chlorophyll-a observations from IMR E-AIMS Bio-Argo float with the Mercator Ocean/Copernicus Marine Service global biogeochemical model.

The model observation comparison for chlorophyll-A profiles shows:

- Weak concentrations in winter due to low light and a deep MLD,
- Increase of the concentration in March, with homogeneous patterns on the 200-300m layer due to mixed layer rich in nutrients but still deep,
- A maximum of chlorophyll in may when the restratification occurs,

- A maximum in subsurface (50-100m) in summer-autumn due to a shallow ML and a surface layer limited by the nutrients.

Observations and model agree quite well and are coherent with the present knowledge on the model error.

OGS also conducted a comparison of the observed chlorophyll profiles with the OGSTM-BFM biogeochemical model coupled off-line with the NEMO physical model over the Mediterranean Sea. The correlation between model and float data is almost always higher than 0.6 showing that the model can reproduce quite well the shape of the vertical profiles of chlorophyll. The assimilation of physical profiles also improves the model accuracy for 8 out of 10 floats.

The examples presented here show the efficiency of the overall system from testing new instruments, launching floats and sending in real time the information so it can be used by GMES/Copernicus Marine service for assimilation and/or validation after a proper QC.

Task 6.3: Impact and use for satellite Cal/Val (Task leader: CLS)

The deliverable (D6.631, Use and impact of new floats for satellite Cal/Val) has been delivered. It presents results from the use and the impact of the new floats deployed as part of E-AIMS for satellite Cal/Val of each satellite variables: altimetry, SST, SSS and Ocean color. 12 floats were available for altimetry, six for SST, seven for SSS and five for ocean color.

Main outcomes for altimetry show that Argo in-situ measurements are useful to assess altimeter mission performances and that the results are sensitive to the use of additional recent data, including E-AIMS floats. The impact of using Argo profiling floats reaching deeper level (4000 dbar) has also been tested. Indeed, in-situ DHA provide the steric height of the water column between the surface and the reference depth of integration of the in-situ temperature and salinity profiles whereas altimeter SLA include the steric signal of the total water column. Thus, the use of deep vertical profiles provides measurements more in agreement with altimeter SLA, which should improve the altimeter quality assessment. Two deep floats have been available within the E-AIMS project (WMO 6901631 and 6901632 (see figure 6.3.1)) and we have compared the associated DHA referenced at various depths with the collocated altimeter SLA. These floats have been launched at mid-latitudes where the steric signal can be found at great depths, as in the Southern Ocean where we have already demonstrated that deep reference level is also required for comparison with altimetry (see WP4 E-AIMS deliverable D4.413). The statistics of the comparisons clearly indicate that steric signal is sampled below the 2000 dbar reference level usually used for Argo floats. This increases the correlation and standard deviation of the differences between altimeter and in-situ data. It is thus definitely recommended to use such deep floats for the altimeter quality assessment.

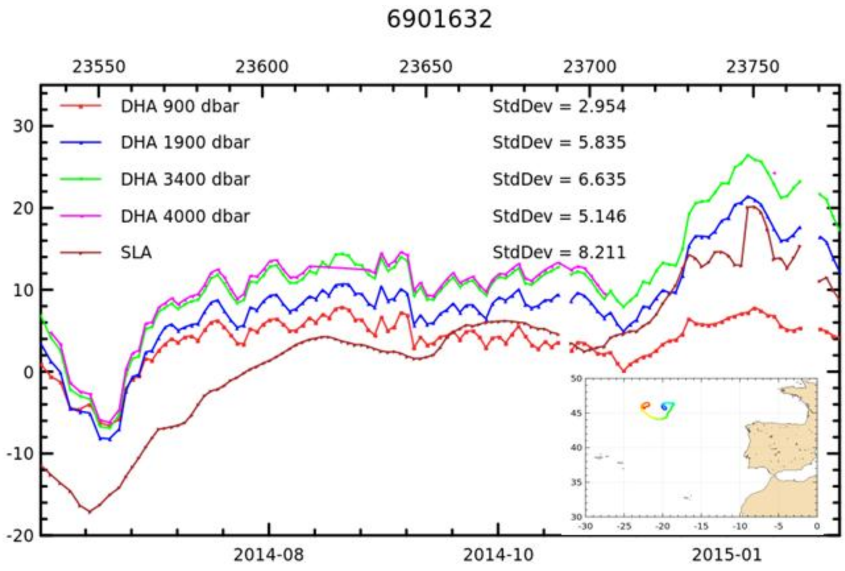

Figure 6.3.1: Time series of the DHA derived from the profiles of float WMO 6901632 with different reference levels of integration varying from 900 dbar (red), 1900 dbar (blue), 3400 dbar (green) down to 4000 dbar (magenta) together with the collocated altimeter SLA (brown).

For SST, the aim of the work was to assess the use and impact of the new E-AIMS floats on validation of SST analyses, OSTIA and GMPE. The matchups between individual E-AIMS floats and each of the SST analyses were calculated, together with the associated monthly statistics. The statistics of the matchups calculated using all available E-AIMS floats were then compared to the statistics using previously deployed Argo floats on a global scale, which was a routine validation of SST analyses using Argo floats. A total of six E-AIMS floats with 186 profiles were identified during the period of January – July 2015. Five of the E-AIMS floats report a profile every four or five days instead of the traditional nine or ten days cycle, which can potentially increase the number of profiles available for statistical analysis. The monthly statistics for the matchups of individual float show that the observations from these floats compared slightly better to the GMPE median than OSTIA. The observations from most of the new floats are warmer than OSTIA, except for float 6901878. Observations from float 6900889 and 6900890 are generally warmer than GMPE median whilst observations from the other floats vary around the GMPE median and slightly colder than GMPE median over the whole period. It is worth noting the monthly statistics for individual floats suggested that the variation is largest for float 6902042 and float 7900591, though the statistics for the latter is dominated by the values for May.

The overall monthly statistics using all E-AIMS floats compared well with those calculated using previous Argo floats on a global scale. The observations are generally warmer than OSTIA and the GMPE median (~0.25 K and ~0.15 K, respectively). The mean differences for E-AIMS-minus-OSTIA/GMPE-median are larger than that for Argo-minus-OSTIA/GMPE-median by 0.15 K/0.1 K. The monthly standard deviations for the former are smaller than those for the latter between February and April, whilst in other months the differences are within ± 0.2 K when comparing against OSTIA and within ± 0.1 K when comparing against GMPE median. Over the whole period, the mean difference (standard error) of the E-AIMS-minus-OSTIA is 0.20 K (0.08 K) and is 0.12 K (0.06 K) when comparing against GMPE median. The standard deviation of the matchups is 0.56 K when comparing against OSTIA and 0.42 K for GMPE median (figure 6.3.2).

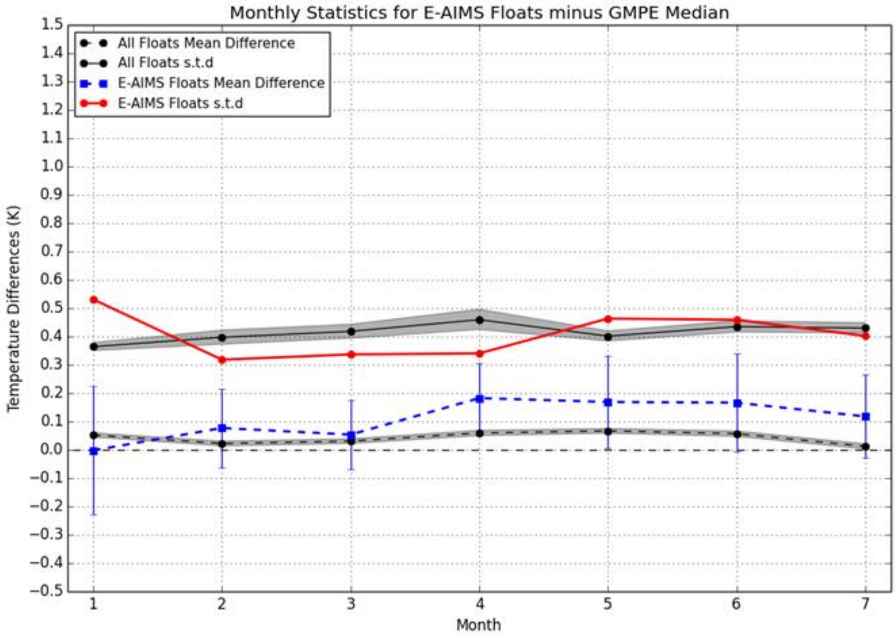

Figure 6.3.2: The monthly statistics of the matchups (E-AIMS-minus-GMPE-median) compared to the statistics using all Argo floats (Argo-minus-GMPE-median) during January – July 2015. Dashed blue line is the mean difference of E-AIMS-minus-GMPE-median, with standard error shown in error bars. Red line shows the standard deviation of the matchups. The dashed black line is the mean differences of the matchups using previously deployed Argo floats, with the gray band showing 95% confidence intervals; the standard deviation is shown in solid black line with the 95% confidence intervals as the gray band.

The statistical assessments show that the new E-AIMS Argo floats have been successfully used to produce validation statistics for operational SST analyses. The performance of these new floats is satisfying as the statistics for the matchups against OSTIA and GMPE median compared well with those calculated using all Argo floats on a global scale. There are near-surface measurements from the new E-AIMS floats, which can be a good addition to the current Argo NST database for validation of the OSTIA diurnal analysis.

Main results for SSS show that in most of the cases, SMOS has a negative bias by respect to Argo in-situ E-AIMS floats (figure 6.3.3). The negative bias of SMOS has been explained by the effect of the elevated land-sea brightness temperature contrast that has not been correctly corrected yet. In the case of the float 6902042, deployed at high latitudes, the stability of the salinity data contrasts with the range of variation of the oscillations of the SMOS salinity (SMOS salinity ranges from 33 to 34.5). The presence of such large noise in the SMOS retrievals are linked to the presence of RFI contamination sources in the North Sea, and the effect of wind in the retrieval algorithm. Despite the fact that almost the totality of the E-AIMS floats have been deployed in areas where satellite estimates are poor because of main issues currently present in the SMOS chain of production: RFI identification and attenuation, land-sea contract, high wind regimes and cold surface waters, availability of the new generation of floats would allow to assess the improvements of the retrieval algorithms to solve these various main issues.

For ocean color, all together the five successful deployments of biogeochemical floats in the framework of E-AIMS have allowed to experiment several situations i.e. i) good situation (i.e. as expected) (figure 6.3.4, in Nordic seas) ii) situation where OC vs observations could be used as a reliable QC indicator (Northern Atlantic) and iii) situation where the water column composition does not allow retrieving reliable values for Chlorophyll concentration (Black Sea - however this situation has been warned by one quality indicator). Bio-Argo floats present a large and sound potential of contribution for QC (already in place) and validation of Ocean Color missions. This validation is to be seen as a geostatistical one and is different from previous analysis which generally admits that one measurement could be used as a reference (i.e. error-free is assumed for the in-situ observation). Therefore, the new approach requires considering uncertainties estimates for both contributors to the validation.

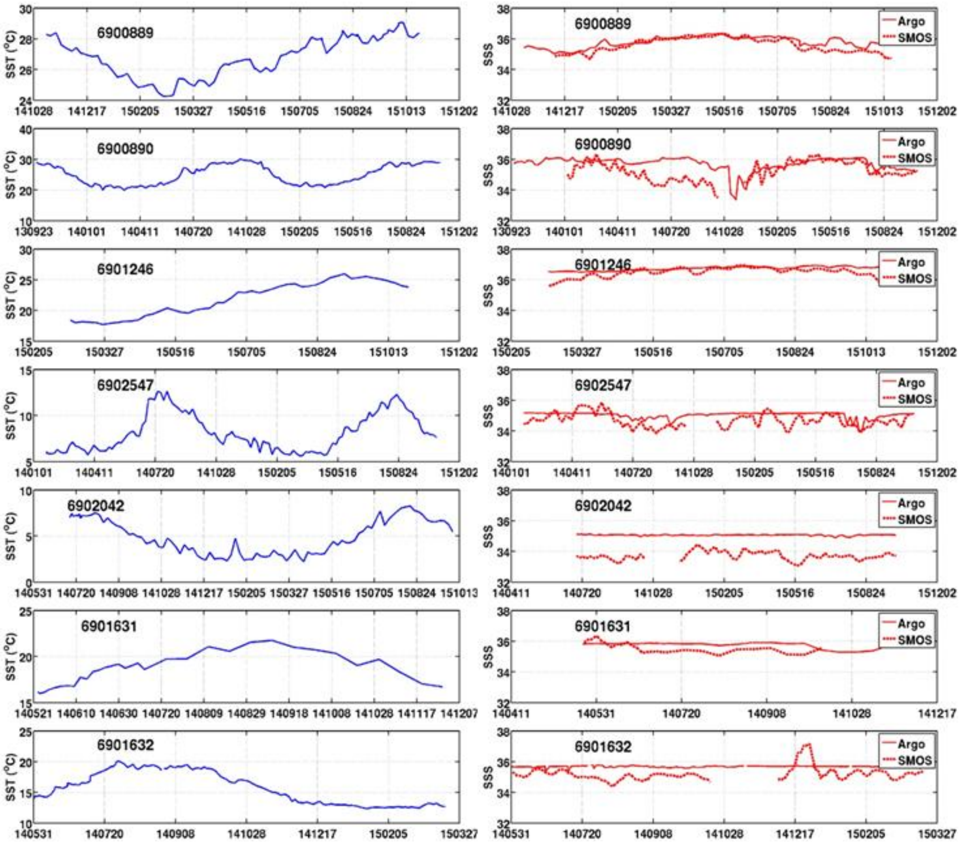

Figure 6.3.3: Time series of SST (left) and SSS (right) for the seven E-AIMS floats used in this work. The right column compares the Argo in-situ estimate with the SMOS salinity estimate.

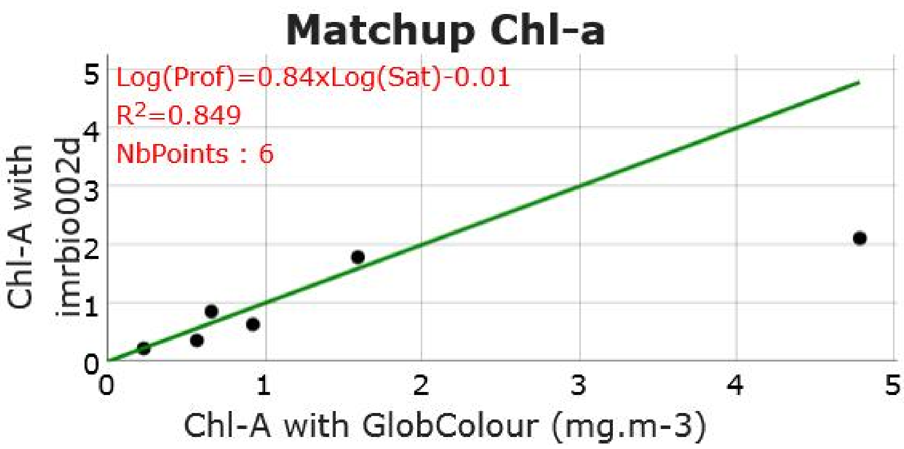

Figure 6.3.4: Biogeochemical floats vs OC matchups for the IMR_bio002 float deployed in Nordic sea

Task 6.4: Final assessment (Task leader: OGS)

E-AIMS organized an end-to-end evaluation of several new Argo floats. European Argo data centers were, in parallel, adapted so that they can handle them (data processing, quality control, data distribution). Observing System Evaluations and Simulation Experiments were conducted to provide robust recommendations for the next phase of Argo and quantify the impact on the Copernicus Marine Service. A real time demonstration of the utility of these new floats for the Copernicus Marine Service was finally successfully carried out.

E-AIMS thus demonstrated the capability of the Euro-Argo infrastructure to conduct R&D driven by Copernicus needs and demonstrated that procurement, deployment and processing of these new floats for Copernicus can be organized at European level. The maturity/feasibility of new float technology (oxygen, Bio-Argo, deep Argo and Arctic) (instruments/sensors, data processing, data quality control, use/uptake by Copernicus Marine Service) was demonstrated and the impact on the Copernicus Marine Service was clearly evidenced. The involvement of the MyOcean and Copernicus Marine Service global and regional monitoring and forecasting centres ensured a full integration of the project R&D results into the operational systems.

Main recommendations from E-AIMS project are to maintain at least the present density of global Argo (with possibly an improved coverage of specific regions such as western boundary currents), maintain Euro-Argo efforts for Mediterranean Sea, Black Sea and Nordic/Arctic Seas and start implementing Deep Argo and Bio-Argo. There is also a need to strengthen the Argo and Euro-Argo data system (real time and delayed mode) (e.g. timeliness for delayed mode QC). Argo and Euro-Argo proposed improvements will have a high impact for the Copernicus Marine Service. They are also essential for Copernicus Climate Service (e.g. deep Argo observations are required to monitor the global ocean heat content which is a fundamental measure of climate change).

Thanks to the comprehensive and very successful R&D activities carried out as part of E-AIMS, the Euro-Argo ERIC is now in an excellent position to agree on and start implementing the new phase of Argo that will be highly beneficial to the Copernicus Marine Service.

WP7 Scientific and technical coordination

(WP leader: partner 1, Ifremer, France)

Activities are reported at the start of this section.

WP8 Communication and dissemination

(WP leader: partner 1, Ifremer, France)

Activities are reported in the next section.