#47

QUARTERLY Newsletter

Mercator Ocean
Ocean Forecasters

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ESA is developing five new missions called Sentinels specifically for the operational needs of the Copernicus (used to be called GMES) program. Sentinel1 (launched in 2013, on the left) and Sentinel3 (launched in 2014, on the right) are the two most important missions for oceanography.

Editorial – Jan/Feb/Mar 2013 – Impact of the loss/addition of satellite altimetry on operational products

Greetings all,

This issue is dedicated to the study of the impact of the loss or addition of satellite altimetry on operational products and systems.

The first news feature by Larnicol et al. is presenting the GODAE OceanView Observing System Evaluation Task Team which primary objective is to support observational agencies by demonstrating the impact of observations on operational forecast and reanalysis systems. Its secondary objective is to improve the performance of operational ocean forecast systems.

The second paper by Labroue et al. is reminding us about the main 2012 events within the satellite altimetry constellation. For the past two decades, we have been used to take for granted the presence of several satellites flying together. The loss of Envisat in April 2012 and the decision to put Jason-1 on its end of life orbit is a crude reminder of this constellation fragility. Hence during 2012, the DUACS and MyOcean Sea Level TAC teams have contributed to secure the altimetry component in the frame of operational oceanography.

The third paper by Labroue et al. is displaying the potential offered by Cryosat-2 for the mesoscale signal. The added value brought by Cryosat-2 as a complement to the existing altimetry constellation is discussed as well as how Cryosat-2 could contribute to secure the altimetry constellation and thus the operational oceanography. Cryosat-2 mission has been introduced into the Near Real Time Sea Level system since February 2012 and has been added to the Delayed Time system in April 2012.

The fourth paper by Remy et al. addresses the impact of the change of the satellite constellation on the French Mercator Ocean analysis and forecasting systems. The impact of the loss of the ENVISAT and Jason1 along track Sea Level Anomaly data in the beginning of the year 2012 in the real time products is studied. A dedicated set of Observing System Experiments (OSEs) is performed and preliminary results are shown. An OSE involves running a copy of an existing assimilation run where some observations are excluded. The difference between this run and the original run assimilating all the observations allows a detailed assessment of the impact the observations have on the assimilation system.

Finally, the fifth paper by Lea et al. is showing a number of Observing System Experiments (OSEs) to assess the impact of the observing network on FOAM, the UK Met Office's ocean assimilation and forecasting system, as part of GODAE OceanView. A parallel version of the FOAM operational system was run, during April 2011, withholding Jason-2 altimeter observations. Withholding Jason-2 removed 43% of the altimeter data and resulted in a 4% increase in the RMS SSH observation-minus-background differences and around ±2ºC small scale changes in 100m temperature as well as around ±0.2 psu changes in surface salinity.

We will meet again in April 2013 for a joint Mercator Ocean/Coriolis issue displaying the latest news about In Situ Observations. We wish you a pleasant reading,

Laurence Crosnier, Editor.

CONTENT

GODAE OCEANVIEW OBSERVING SYSTEM EVALUATION (OSEVAL) TASK TEAM NEWS

By G. Larnicol[1], P. Oke[2]

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Last November (5-9th Nov 2012), the GODAE Ocean View Science (GOV) Team meeting took place in Rio (Brazil). It was an opportunity to present the main achievement done in the frame of GOV program and in particular of the GOV Observing System Evaluation Task team (OSEval TT).

The primary objective of the Observing System Evaluation Task Team (OSEval-TT) is to support observational agencies by demonstrating the impact of observations on forecast and reanalysis systems. The secondary objective of the OSEval-TT is to improve the performance of operational ocean forecast systems. There are five key areas of activity that the OSE TT operates (see figure below). These include:

1. Capability building;
2. Routine monitoring of the Global Ocean Observing System (GOOS);
3. Delayed-mode assessments of the GOOS;
4. Design and evaluation of new and future observing system components; and
5. Provision and dissemination of Observation Impact Statements (OISs) based on OSEval evidence.

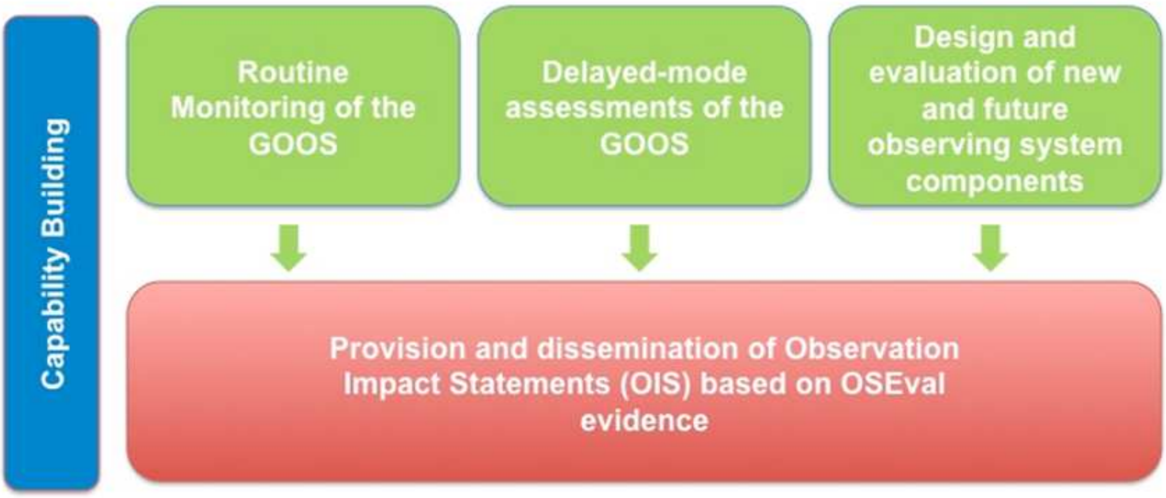

Figure 1: Schematic diagram representing the relationship between the OSEval activities. Capability building (blue) cuts across all OSEval-TT activities, including observing system design and assessment research (green) that feeds into the Observation Impact Statements (OSIs) (red).

Capability Building and Provision of Observation Impact Statement (OIS)

Capability building is a core mission of the OSEval-TaskTeam (TT). The OSEval-TT seeks to empower the research community in order to quantify the impact of observations on analysis and forecast systems and to contribute to the design of future observing system components. This is mainly achieved through international workshops that are hold about every two years. The TT workshops are intended to allow researchers to share and discuss details of the technical and scientific aspects of ocean forecasting and observing system evaluation.

The workshops are also the place for TT members to communicate with observation agencies through the so called Observation Impact Statement (OIS),. Indeed, OISs are the primary mechanism by which the OSEval-TT will communicate findings of the impact of observations on analysis and forecast systems to observational agencies and communities. More concretely, an OIS is a short communication containing a few pages of text with graphics and tables that can be easily understood by people that are not always experts in data assimilation. The OIS will help make a case for continuance of each observational program (i.e. Continuation of Jason-1), and for prioritizing potential changes or enhancements to observational programs.

Since the beginning of the TT, several OIS have been provided to space and in-situ agencies. For instance in the past, evidence of benefits having Jason-1 and Jason-2 interleaved are been provided by UKMettoffice (UK), BlueLink (Austr.) and Mercator Océan (FR) centers.

More recently, in February 2012, results from UKMetoffice NRT OSEs (see next §) are used to help the Royal Australian Navy (RAN) to justify continuance of XBT program (P. Oke, personal communication). Similarly, extension of life of Jason-1 and usefulness of Cryosat-2 data has been justified using the OIS provided by the task team.

Routine monitoring of the Global Ocean Observing System

In order to be able to quickly provide materials with regards to observing system events (i.e. planned or unplanned loss or gain of instruments, for example data outages due to the loss of an altimeter, launch of a new satellite, loss or deployment of Argo floats) the OSEVal-TT has decided to perform routine monitoring of the Observing system through Near-Real-Time (NRT) Observing System Experiments. NRT OSEs involve a parallel run of an operational forecast system, in addition to the standard operational forecast. In each NRT OSE, a single component, or sub-set of a single component, of the GOOS will be with-held from the parallel forecast for a period of one month. This will allow each operational centre to quantify the degradation of the forecast system when the observations are with-held – thereby quantifying the impact of the with-held observations on each forecast system. This activity was performed during the year 2011 by the UKMetoffice Center. A technical report is now available at the following address:

http://www.metoffice.gov.uk/learning/library/publications/science/weather-science/forecasting-research-technical-report (report n° 568: Observation Impact Statement for operational oceanography).

For the year 2013, it is planned that the UKMetoffice and Mercator Ocean forecasting centers will perform again NRT OSEs. More news on https://www.godae-oceanview.org/.

Delayed mode assessments of the GOOS and new/future observing system components

The assessment of the GOOS (existing, new or future) using delayed-mode OSEs is an important part of the OSEval-TT activities. In this context, the TT provides an outline of "best practice" experiment design for OSEs on the TT website, recommendations of the GOOS to be studied: different altimeter or SST constellations, complementarily between ARGO and altimetry, or complementarities between different in-situ observing system (XBT, ARGO, moorings, drifters, tide gauges). It also provides a forum for presenting results at TT workshops that will be then included in relevant OISs for circulation.

The GODAE Ocean View Science Team meeting (hold in Rio in November 2012) was the opportunity to review the work performed by the member team. The studies are divided into two categories. The first one consists in leading standard OSE/OSSEs*** (with holding some data) whereas the second categories consist in developing new or alternative approaches that essentially aims at reducing the cost of the OSE/OSSE studies. In this case, TT members have developed method such as Degree of Freedom Signal (TOPAZ (Norway), CSIRO (Aust.), Mercator Ocean (Fr), CLS (Fr)), forecast sensitivity diagnostics (NRL, US), observation footprint (CSIRO, Austr.).
The TT is very active and provided a significant contribution to the 20 years of Progress in Radar altimetry symposium and 4th ARGO Science Workshop (http://www.altimetry2012.org/). The list of GOV OSEval TT contribution is given below:

- Dombrowsky et al. (Mercator Ocean, Fr) GODAE OceanView**:** Towards a Long-term International Program for Ocean Analysis and Forecasting
- Oke et al. (CSIRO, Austr.) – The dependence of short-range ocean forecasting on satellite altimetry
- Remy (Mercator Ocean, Fr) - Observation Sensitivity Studies at Mercator Océan: a Contribution to GODAE OceanView
- Greiner et al. (Mercator Ocean/CLS, Fr): Evaluation of Real Time and Future Forecasting Systems at Mercator Océan: Overview and Recent Improvements at the Global and Regional Scales.
- Oke et al.(CSIRO, Austr.) – Developing OISs under GODAE OceanView
- Lea et al. (UKMetoffice, UK) – Using observing system evaluation experiments to test the value of Argo data in FOAM
- Cummings et al. (NRL, UK) Impact of Assimilation of Argo Data in Global HYCOM
- Benkiran (Mercator Ocean/CLS, Fr) Impact of Argo data in Mercator Ocean global and regional systems
- Fuji et al. (JMA/MRI, Japan) Evaluation of the Argo float impacts on the ocean data assimilation systems in JMA/MRI

Conclusion

Several studies (both routine monitoring and delayed assessment of the GOOS) presented at these workshops and symposia demonstrate the interest to gather and to compare the results obtained by the different groups. Despite, the impact or the value of one or more observation types could be system dependant or could depend from the approach (standard OSE/OSSE or alternative approaches), the overall results and recommendations coming from the GOV OSEval–TT member are consistent and confirm the key and complementary role of the space (altimetry, SST) and in-situ (in particular ARGO) data. A full review of the main achievement done in the frame of the GOV OSEval-TT will be given at the GODAE final symposium (4-6 November 2013, Washington DC).

*** : Definition of OSE/OSSE:

OSE: an Observing system Experiment consists in using real data and withdraw or keep components of the observation system in parallel assimilation run and measure the impact. The truth is unknown, and there is a need for an external assessment protocol (for example use of independent observations). The OSE allows assessing the relative impact of existing observing systems on analysis and forecast produced by a given assimilative system

OSSE: an Observing System Simulation Experiment consists in using simulated data instead of real data. In this case, the truth is simulated, and assumed to be known (identical/fraternal twin experiments). OSSE allows assessing the potential impact of future observing systems. – Results depend on the experimental protocol, and the confidence one may have in quality of the observations simulation. Results have to be consolidated afterwards with real data.

DEATH AND BIRTH IN THE ALTIMETRY CONSTELLATION

By S. Labroue[(1)], F. Briol[(1)], Y. Faugère[(1)], G. Dibarboure[(1)], I. Pujol[(1)], G. Larnicol[(1)], E. Bronner[(2)], T. Guinle[(2)], T. Parrinello[(3)], P. Féménias[(3)]

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Abstract

The operational oceanography relies on in situ observations but also on space components. Altimetry is one of the main components of such an operational system. For the past two decades, we have been used to take for granted the presence of several satellites flying together. The loss of Envisat in April 2012 and the decision to put Jason-1 on its end of life orbit is a crude reminder of this constellation fragility.

Especially during 2012, the efforts of the DUACS and Sea Level TAC teams have contributed to secure the altimetry component in the frame of operational oceanography. We present here several results to highlight the impact of the loss of ENVISAT and the change of orbit for Jason-1.

Introduction

The multi-mission processing of altimeter data was developed by CLS as part of D.U.A.C.S (Developing Use of Altimetry for Climate Studies), a European Commission project which started in February 1997. DUACS was a shared cost project, part-funded under the CEO Program of the Environment and Climate. It was coordinated by CLS and gathered four of the major climate research teams in Europe: ECMWF, U.K.Met.Office, Cerfacs and the Max-Planck Institute for Meteorology. The 3-year project's purpose was to demonstrate that climate applications could be operationally served by multi-mission altimetry data in near real time.

Since the end of the original project, the Near Real Time (hereafter NRT) and Delayed Time (hereafter DT) components have continued to serve operational oceanography and climate forecasting projects. Thirteen years after the original prototype, the system has been redesigned and significantly upgraded many times as the knowledge of altimetry processing has been refined and as oceanography needs to evolve. It is now part of the CNES multi-mission ground segment SSALTO. It is also the backbone of the Sea Level Thematic Assembly Center of the European project MyOcean, and it provides data and algorithms to ESA's Climate Change Initiative.

DUACS features multi-mission products based on all altimetry satellites from GEOSAT to Jason-2 for a total of 60 years of cumulated data. In Near Real Time, the system's primary objective is to provide operational applications with directly usable high quality altimeter data from all missions in operations. In Delayed Time, it is to maintain a consistent and user-friendly altimeter climate data record using the state-of-the-art recommendations from the altimetry community.

DUACS is an operational production system and serves the operational oceanography needs by adapting the system very quickly to any change in the operational altimetry constellation

At the beginning of 2012, the multi mission system relied on Jason-2, Jason-1, Envisat and Cryosat-2 that was introduced in February 2012. Jason-1 and Jason-2 orbits were optimally phased for the mesoscale observation in Near Real Time as described in Dibarboure et al 2011a . Envisat was on its drifting orbit since October 2010.

Jason-1 and Envisat, the two older satellites of the altimeter constellation, have been impacted by severe anomalies at the beginning of the year 2012. Jason-1 has suffered 3 safe hold modes, inducing mission unavailability between 2012/02/16 and 2012/02/29 and since 2012/03/03. Additionally, on 8 April, the communication links with the Envisat satellite were suddenly lost, preventing reception of telemetry data, and inducing unavailability since this date. Regarding Envisat, efforts to resume contact with the satellite have not been successful and the end of this mission was declared a few weeks later.

Regarding Jason-1, CNES/NASA decided to move Jason-1 from its current repeat orbit to a drifting orbit, in order to avoid the risk of a definitive failure on its repeat track orbit. The operations for changing Jason-1 on its new geodetic orbit were conducted in April and the Jason-1 mission came back into DUACS system in May, 25 2012.

Impact of the Envisat loss and Jason-1 orbit change on the altimetry products

There are several indicators to assess the impact of a change in the altimetry constellation. Indeed, the loss of Envisat and interruption of Jason-1 time series for a while has an impact on the availability of the along track data that are assimilated in the forecast models. Another indirect mean to quantify the state of the altimetry constellation is the assessment of the quality of the merged product (the multi mission map of sea level anomaly, MSLA). We present here two global indicators and a geographic assessment of the impact on the maps.

Figure 1 shows the time series of the mean error on the MSLA map. This error represents the formal error which is derived from the optimal interpolation processing used for the mission merging (LeTraon 2003). The monitoring of the mean error on the global products exhibits several interesting features. As expected the lowest level is found when 4 satellites are available during a few days, between the introduction of Cryostat-2 and the loss of Jason-1. The larger level of error is observed when only 2 satellites are available (Jason-2 and Cryosat-2) between Envisat loss and Jason-1 recovery. Between February, 16 and April, 8, the global product mainly relies on Jason-2, Envisat and Cryosat-2 and the error is increased by 2%, compared to the 4 satellites configuration. Since the introduction of Jason-1 on its geodetic orbit, the error is close to 24%, a level slightly higher than the one obtained with Jason-2, Envisat and Cryosat-2. This difference is due to the weight of the high latitudes that were covered by Envisat decreasing the global error whereas they are not covered by Jason-1 in the current satellite configuration. If the high latitudes are removed from this average, the current configuration with Jason-1 provides less error than the Jason-2/Cryosat-2/Envisat configuration (not shown) because Jason-1 payload is considered as being more accurate than Envisat mission due to the loss of the second frequency on Envisat which happened in January 2008.

This curve shows that the introduction of Cryosat-2 allowed a significant improvement at the beginning of the year and mitigated significantly the loss of Jason-1 and Envisat between April, 8 and May, 25.

Although, the current quality of the Jason-2 and Cryosat-2 along track products remains at the same level, the loss of Envisat, accentuated by a long unavailability of Jason-1 induces a strong decrease of the capacity of the constellation to sample correctly the ocean sea level. We observe that the quality of the map products is significantly degraded, as expected from previous study (Pascual et al., 2006; Le Traon et Dibarboure, 1999).

The blue line and the red line give two examples of the error over two regional products, respectively the Mediterranean Sea and the Black Sea. The error increase is several times higher than for global ocean. This is explained first by the fact that a restricted area is more sensitive to the lack of sampling which is not regularly distributed. Secondly it is due to the lower a priori correlation scales used for the Sea Level (SLA) estimation in these regions

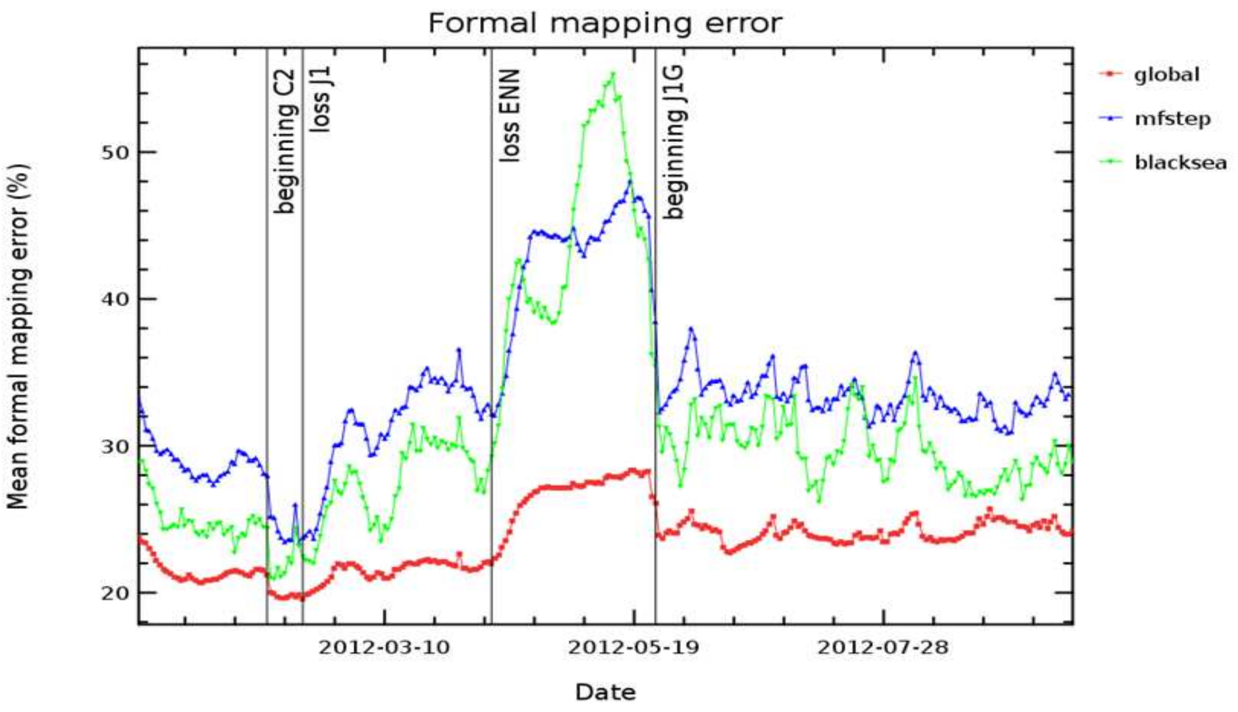

Figure 1: Mean formal error (in percentage of the signal variance) of the multi mission map of sea level anomaly from January 2012 till September 2012. The error is shown for the global product (red) and regional products over the Mediterranean Sea (blue) and Black Sea (green).

Figure 2 shows the time series of the mean contribution of each satellite for the computation of a multi satellite merged global product. This component is an indicator to assess the weight of each mission in the merging process. The full method to compute this contribution is detailed in Dibarboure et al. (2011a). This parameter mainly takes into account the accuracy of the satellite, but also its sampling capabilities in Near Real Time.

It is another way to quantify the contribution of a given satellite in the altimeter constellation throughout the year, as Cryosat-2 for instance. At the beginning, in the 4 satellite configuration, the contribution of Cryosat-2 was quite low at a level of 12% and then it increased with the successive unavailability of Jason-1 and loss of Envisat up to 35% during the Jason-2/Cryosat-2 configuration. Since May, its contribution is in averageat a level of 25%.

Another interesting feature given by these curves is the respective contribution of each satellite. In early February, the operational real time sea level observations were provided by four satellites (Jason-2 and Jason-1 on their repeat orbit, plus Envisat and Cryosat-2 on their geodetic orbit). Jason-2 and Jason-1 yield the same contribution while Envisat and Cryosat-2 have a lower weight in the map, due to their drifting orbit, and the lack of a precise dual frequency ionospheric correction. During Jason-1 unavailability, Envisat and Cryosat-2 contribution increases nearly at the same level. Finally, when Jason-1 comes back into the merging processing on its geodetic orbit, its contribution is lower by 5% compared to the reference mission, due to its new orbit.

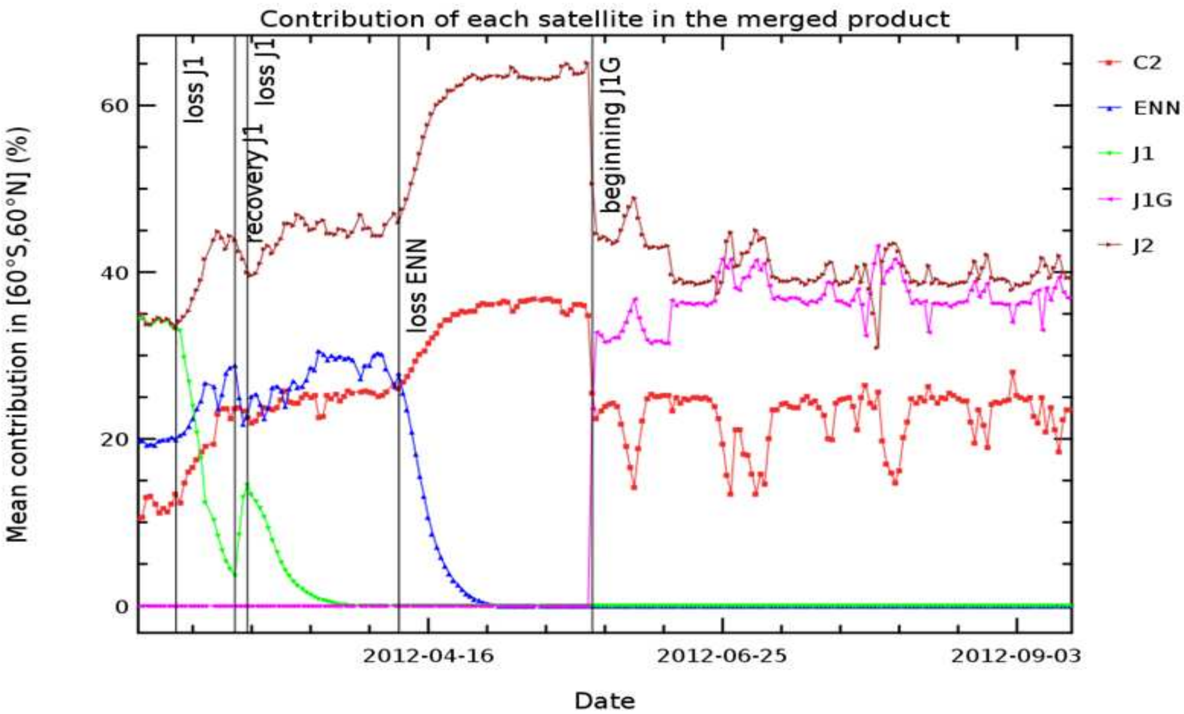

Figure 2: Mean contribution (in percentage) of each satellite in the multi mission map of sea level anomaly from January 2012 till September 2012 for Cryosat-2 (red), Envisat (blue), Jason-1 repeat track orbit (green), Jason-1 geodetic orbit (pink), Jason-2 (brown). The contribution is calculated between 60° S and 60°N.

The two indicators discussed above are global indicators but they do not show how the error is geographically distributed. Figure 3 shows the map of the formal error for three different satellite configurations to illustrate the geographical error variation induced by a change in the constellation.

The upper panel exhibits the optimal configuration given by the 4 satellites, which represents the minimum of error that can be achieved in Near Real Time. As explained by Dibarboure et al. (2011b), Cryosat-2 can provide precious information but cannot completely replace Jason-1 (or Envisat) for mesoscale observation as it was not fully designed for operational oceanography regarding sampling performance or measurement precision. When Envisat and Jason-1 are not used in the mapping process, the error (middle panel) is locally multiplied by a factor 5, at mid latitude notably for areas that are in the mean time far from Jason-2 track (inter-track or above 66° of latitude) and where Cryosat-2 geodetic orbit induce a degraded sampling. When Jason-1 recovers, the error shows an intermediate level (bottom panel), especially in the regions of low variability as the Eastern part of the North Pacific. In most of the regions between 60°N-60°S, the error level is close to the one featured by the 4 satellite configuration but the trackiness is more present on the 3 satellite configuration map, leading to a locally increased error.

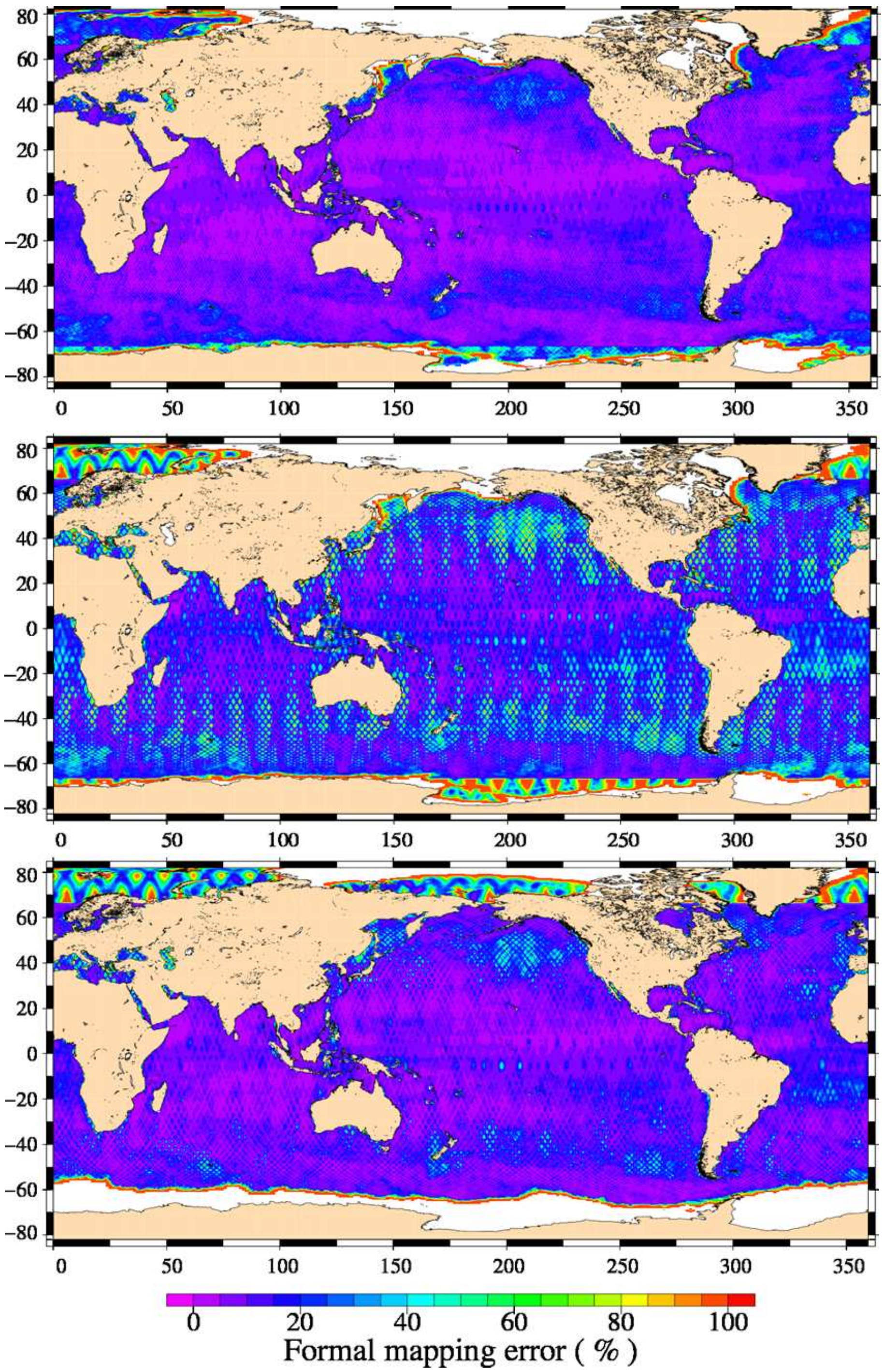

Figure 3: Map of the formal error (in percentage of the signal variance) of the multi mission map of sea level anomaly for Jason-2/Jason-1/Envisat/Cryosat-2 configuration (upper panel), Jason-2/Cryosat-2 configuration (middle panel) and Jason-2/Jason-1 Geodetic/Cryosat-2 configuration (bottom panel)

The future

This is the first time since the beginning of satellite merging that the operational altimetry constellation relies on only one repeat track satellite. In the past, we have always had at least two repeat track orbits (the historical Topex/Jason-1/Jason-2 10 day orbit complemented by the 35 day orbit from ERS /Envisat). We see here that the 2 geodetic orbits contribute significantly to the quality of the altimetry products and help to secure actively the operational constellation.

Nevertheless, there is a strong probability to loose Jason-1 mission in the coming months and to come back to the level of error displayed on the middle panel of Figure 3. Indeed Jason-1 mission has overcome twice its extended life span, since it has been in orbit for more than 11 years. Even if all the on board sensors are performing nominally, the probability to meet a failure is growing.

Furthermore, we have to remind that Cryosat-2 is not part of GMES and is only a mission of opportunity for operational oceanography. Beside some problems on the satellite platform that can always happen, the limitation of the funding efforts could also be possible focusing the efforts on the mission objectives rather than oceanography and the contribution of Cryosat-2 cannot be taken as granted.

The altimetry constellation is in a very fragile state and all tracks are being studied to further secure the availability of data.

First, a Chinese mission HY-2A is currently flying on a 14 day repeat track orbit. HY2A was launched in August 2011 and its payload is optimized for ocean with a dual frequency altimeter and a radiometer. This mission has a great potential to complement the Jason-2 reference mission. Data quality has been assessed (Legeais et al 2012) but unfortunately the do not meet the requirements to be used in the DUACS processing. The data still suffer from too large errors to be used in the merging processing. Hopefully, one can expect that the quality will be improved within a few months.

The other perspective is the launch of AltiKa scheduled in February 2013. This mission flies on ERS/Envisat ground track, covering the high latitudes. This is an innovative mission that embarks an altimeter in Ka band which should improve the along track resolution.

In a longer future, the Jason-3 mission will replace Jason-2 reference mission with a launch currently scheduled in 2014. This will greatly secure the constellation by rejuvenating the reference mission on one hand and on the other hand by changing Jason-2 orbit to reproduce the optimally phased tandem offered by Jason-2 and Jason-1 during a few years.

Conclusion

The year 2012 was a rich year full of events for altimetry, with the loss of Envisat, the change of orbit of Jason-1 and the introduction of Cryosat-2 mission into the DUACS system. A lot of efforts have been made to maintain the quality of the operational services, throughout the year.

Several results emphasize here the need for altimetry data and remind that the state of the altimetry constellation is very fragile. Within a few weeks, the situation changed from an optimal situation with 4 satellites up to a critical situation of the ocean being sampled by 2 satellites. The situation could even have been worse if Cryosat-2 mission had not been ingested into the multi satellite processing, thanks to joints efforts between space agencies (CNES, ESA,NOAA), DUACS and Sea Level TAC teams and operational users.

The future is not yet completely secured and the coming months will be critical depending on the success of AltiKa mission (launch and data quality) and on the capacity to improve the quality of the HY2A data.

Acknowledgements

This work was co-funded by the CNES (SALP project) and the MyOcean Project (WP11 - Sea-Level Thematic Assembly Center).

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AN EVENTFUL YEAR IN THE ALTIMETRY CONSTELLATION

By S. Labroue(1), F. Briol(1), G. Dibarboure(1), I. Pujol(1), F. Boy(2), N. Picot(2), T. Parrinello(3), P. Féménias(3)

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Abstract

The Cryosat-2 mission is dedicated to cryosphere study but is also an opportunity mission for ocean. This paper presents the different results obtained thanks to the addition of Cryosat-2 in the altimetry operational constellation, both for Near Real Time and Delayed Time products.

Introduction

The multi-mission processing of altimeter data was developed by CLS as part of D.U.A.C.S (Developing Use of Altimetry for Climate Studies), a European Commission project which started in February 1997. DUACS was a shared cost project, part-funded under the CEO Programme of the Environment and Climate. It was coordinated by CLS and gathered four of the major climate research teams in Europe: ECMWF, U.K.Met.Office, Cerfacs and the Max-Planck Institute for Meteorology. The 3-year project's purpose was to demonstrate that climate applications could be operationally served by multi-mission altimetry data in near real time.

Since the end of the original project, the Near Real Time (hereafter NRT) and Delayed Time (hereafter DT) components have continued to serve operational oceanography and climate forecasting projects. Thirteen years after the original prototype, the system has been redesigned and significantly upgraded many times as the knowledge of altimetry processing has been refined and as the oceanography needs evolved. It is now part of the CNES multi-mission ground segment SSALTO. It is also the backbone of the Sea Level Thematic Assembly Center of the European project MyOcean, and it provides data and algorithms to ESA's Climate Change Initiative.

DUACS features multi-mission products based on all altimetry satellites from GEOSAT to Jason-2 for a total of 60 years of cumulated data. In Near Real Time, the system's primary objective is to provide operational applications with directly usable high quality altimeter data from all missions in operations. In Delayed Time, it is to maintain a consistent and user-friendly altimeter climate data record using the state-of-the-art recommendations from the altimetry community.

DUACS is an operational production system and serves the operational oceanography needs by adapting the system very quickly to any change in the operational altimetry constellation. Cryosat-2 mission was not designed for oceanography, but is an opportunity mission that turned out to contribute very efficiently to the quality of the altimetry products en 2012. This paper shows what are the different achievements realized for the mesoscale observation thanks to Cryosat-2.

The Cryosat-2 mission

The Cryosat-2 mission has been designed in order to determine fluctuations in the mass of the Earth's major land and marine ice fields thanks to continuous measurements of Earth's land and marine ice fluxes (Wingham et al, 2006; Drinkwater et al, 2004).

Cryosat-2 was launched on April 2010 into a near circular, near polar orbit with an average altitude of 717.2 km. The orbit inclination is 92°, which is a compromise between the desire to achieve a high density of orbit cross-overs at high latitudes (for land ice altimetry), while having more-or-less complete coverage of the Arctic Ocean and the Antarctic continent. The repeat period is 369 days which provides the high orbit cross-over density. The orbit also has a 30-day subcycle, which provides every 30 days a uniform coverage of the Arctic sea-ice. (The term 'subcycle' means that the full, 369-days repeat is built up by successive shifts of the 30-day repeat pattern.)

Much progress has been made in the determination of mass fluxes, in some special cases, by the use of radar altimeter data from ERS-1 and ERS-2 (Wingham et al, 1998). In order to extend these results to regions extensively covered by sea-ice and to the margins of the ice sheets, respectively, it is necessary to improve the spatial resolution of the altimeter measurement system.

The primary payload of Cryosat-2 is a radar altimeter operating in Ku band (13.575 GHz) with these additional capabilities. This radar is capable of operating in a number of modes, optimised for measurements over different surfaces. A conventional, pulse-width limited, low-resolution mode (LRM) provides the measurements over the central regions of the ice sheets, to continue the ERS and ENVISAT measurement series. This mode is also used over oceans for the major ocean basins. The SAR (Synthetic Aperture Radar) mode will enable an enhancement of the spatial resolution along track, and this mode is used over sea-ice to retrieve measurements over relatively narrow leads of open water which would be indistinguishable in low-resolution mode (Raney et al, 1998). Over the topographic surfaces of the ice-sheet margins this SAR mode is enhanced by interferometric operation across-track so that the arrival angle of the echoes may be measured.

Even though the Cryosat-2 mission has been primarily designed for cryosphere observation, all data acquired over ocean are, in theory, valuable for the observation of oceanic circulation and mesoscale variations. But in coherency with the mission's primary objectives, Cryosat-2 payload is not optimal for oceanic observation for three reasons:

1. Firstly, the altimeter on board Cryosatis a single frequency altimeter: it does not have a second radar frequency (as opposed to ENVISAT and Jason-2), so there is no instrumental correction for the range delay induced by the ionosphere.
2. Moreover, there is no microwave radiometer to provide an accurate correction for the range path delay due to propagation of the radar signal through the troposphere.
3. The last feature deals with the orbit, which is not optimal for ocean observation, since the exact repeat cycle is too long and the sub cycle of 30 days is not optimized for the ocean sampling in real time. Indeed, due to the sub cycles of 2 and 30 days of Cryosat-2 orbit, the whole oceans are covered by patches of orbits inequally distributed (Dibarboure et al, 2011 b), instead of providing a uniform coverage required for Near Real Time applications to resolve mesoscale dynamics, as provided by repeat track Jason missions.

Dibarboure et al (2011b) have first showed the potential offered by Cryosat-2 for the mesoscale observation through dedicated experiment, based on preliminary Cryosat-2 data sets. They discussed the added value that would bring Cryosat-2 as a complement to the existing altimetry constellation flying at that time (based on Jason-2, Jason-1 and ENVISAT) and how Cryosat-2 could contribute to secure the altimetry constellation and thus the operational oceanography.

Since then, Cryosat-2 mission has been introduced into the Near Real Time system since February 2012 and has been added to the Delayed Time system in April 2012. While the ESA official products over ocean still suffer some anomalies, the Cryosat-2 data availability is based on a CNES prototype (CPP ie CNES Processing Prototype) that provides data to the DUACS system on a best effort basis.

Contribution to the mesoscale observation

The most critical issue when adding a new mission in the DUACS system is the introduction into the merging processing. The Cryosat-2 along-track SLA data were merged into a gridded product (map) using Objective Analysis as in Ducet et al (2000) or Dibarboure et al (2011a). Two sets of parameters are relevant for this merging: the statistical description of the topography signal to reconstruct, and the observation error covariance associated with each dataset.

The mesoscale signal description is geographically dependent (derived from Le Traon et al (2003)) while the covariance models used as a statistical error description for along-track datasets are geographically dependent and mission dependent.

For drifting orbit missions and thus for Cryosat-2, it is impossible to use the repeat track analysis, because we do not have a precise reference profile computed from the average of a long time series of co-located measurements. The alternative is to use a generic gridded mean sea surface (MSS) but this process involves higher residual errors (Dibarboure et al, 2011b). The typical error range is 1 to 3 cm RMS with peaks higher than 10 cm. The gridded MSS is therefore only a "proxy" of the classical mean profile used in the repeat track analysis. For this experimentation, the MSS used is the CNES/CLS 2011 (Schaeffer et al, 2010).

Cryosat-2 error covariance matrices were set up with additional error sources to account for gridded MSS error residuals, wet troposphere error residuals and ionosphere error residuals. The practical consequence of these additional errors is that the optimal interpolation does not "trust" Cryosat-2 as much as it trusts the Jason-2 mission. This point is significant to obtain realistic global mesoscale mapping with Cryosat-2.

The following examples illustrate the results obtained with the addition of Cryosat-2 in the constellation, at global and regional scales, in Near Real Time and Delayed Time configurations.

Figure 1 presents the difference of map obtained between a 3 satellites configuration (given by Jason-2, Jason-1 and ENVISAT on their repeat track orbit) and a four satellite constellation when adding Cryosat-2 created in near real time (NRT) mode, i.e. using only data from the past.

As already mentioned, the main weakness of Cryosat-2 for oceanography is the sampling pattern shown in Figure 1 (upper panel). The non-zero differences are aggregated near recent Cryosat-2 measurements. Recent is subjective and in this case dictated by the Optimal Interpolation decorrelation scales (Le Traon et al, 2003). For the sake of simplification, if we assume an average temporal decorrelation of 15 days, the non-zero differences are aggregated exactly like a 15-day sampling from Cryosat-2. The band-shaped aggregation is not stationary and it propagates in the westwards direction at about 50 km/day. In these bands, the magnitude and shape of the eddies are better retrieved, especially in the regions of strong mesoscale activity. Another improvement is observed at high latitudes where Cryosat-2 adds precious information in these regions sampled only by ENVISAT.

Cryosat-2 sub-cycles (i.e. a near repeat cycle with homogeneous global coverage) are at 2 and 30 days only. This amplifies the observation gaps or “blind spots”: the properties of Cryosat-2 orbit make it impossible to get a globally homogeneous sampling of the ocean in a 10 to 20 day period associated with mesoscale decorrelation scales (Jacobs et al, 2001; Le Traon et al, 2003). Cryosat-2 sampling pattern is exceedingly irregular when it comes to observing mesoscale in NRT. Figure 1 shows that good sampling zones (i.e. wherever Cryosat-2 improves multi-altimeter maps) are made of 500 km blocks of recent satellite tracks interleaved with 500 km wide observation gaps (satellite tracks too old to be an asset).

However, for offline products where data from the map’s future can be used, this limitation is less critical. It is possible to benefit from a ± 15 day range centered on the map date, i.e. from a full 30-day sub-cycle (globally homogeneous sampling). Cryosat-2 delayed time sampling is substantially more regular, thus increasing the value of this altimeter for offline mapping. The caveat for using the offline sampling is the risk of mesoscale aliasing which is created by the westwards propagating nature of the 500 km bands (as opposed to the stable sampling pattern of the Jason tandem described by Dibarboure et al, 2011a).

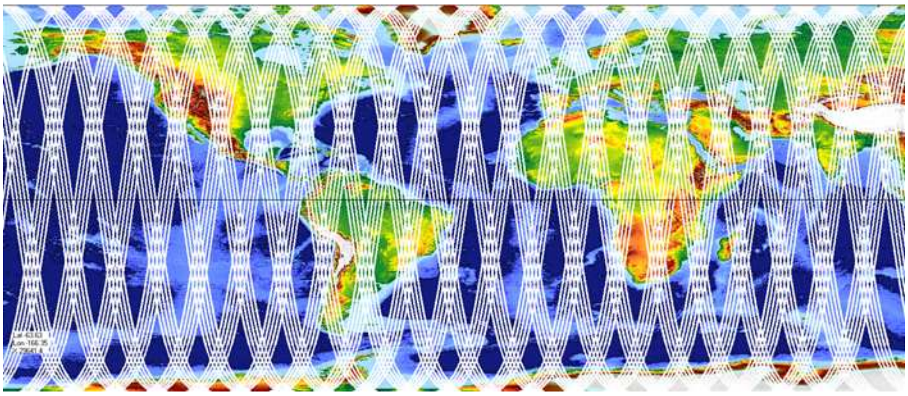
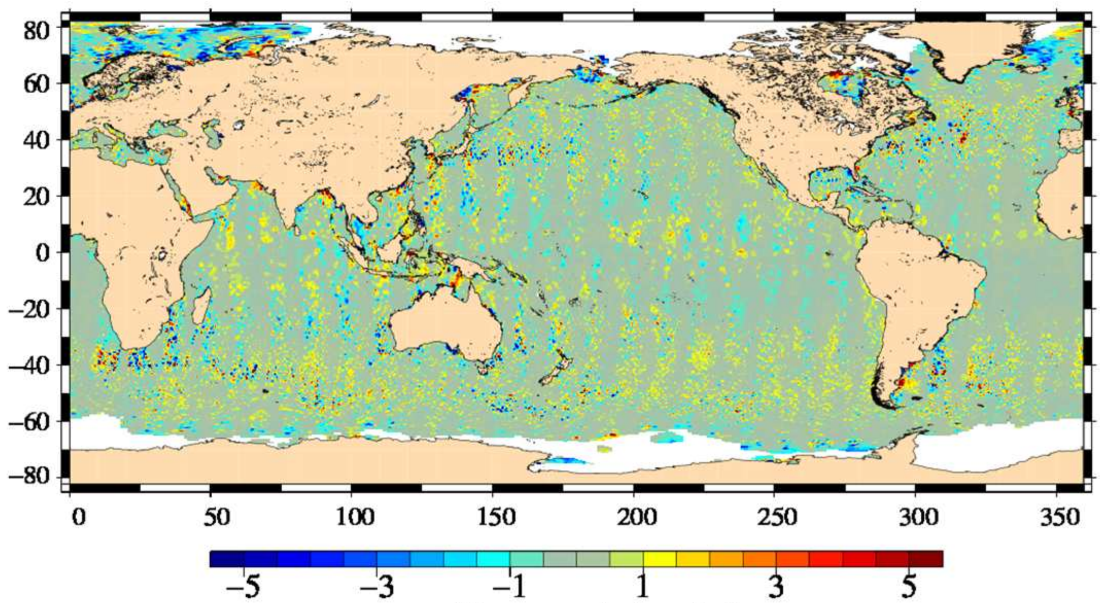


Figure 1: The lower panel shows the difference (cm) between a 3 satellite MSLA map (Jason-2, Jason-1 and ENVISAT on their repeat track orbit) and a 4 satellite MSLA map (Jason-2, Jason-1 and ENVISAT on their repeat track orbit and Cryosat-2). The contribution to the mesoscale observation is observed along the Cryosat-2 tracks. The upper panel shows the Cryosat-2 tracks obtained over a 15 day time span.



The Cryosat-2 mission provides a great contribution in smaller basins such as the Mediterranean Sea and the Black Sea since it provides a larger density of observations in regions where the oceanic structures have smaller spatial scales than in the global ocean.

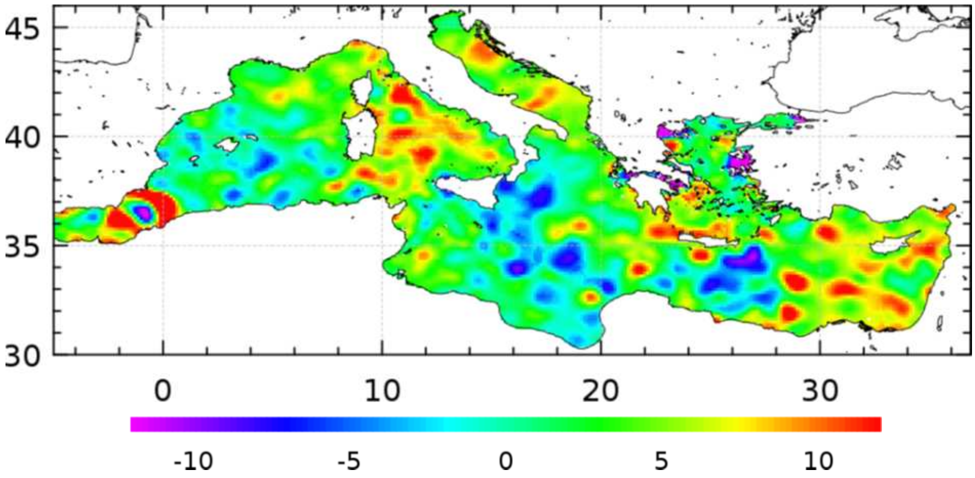


Figure 2: MSLA map in cm (Jason-2, Cryosat-2 and Jason-1 on its repeat track orbit) from the regional Delayed Time product over the Mediterranean Sea

There is a nice example of the contribution of Cryosat-2 in the Alboran Sea. The map of Sea Level Anomaly from merged satellites (Jason-2, Jason-1 on its drifting orbit and Cryosat-2) on Figure 2 shows a strong eddy which has a large magnitude in this basin, but represents quite small structures (50 to 100 km diameter) to be detected by altimetry. Figure 3 exhibits the maps of ocean color and Sea Surface Temperature at the same time tag, which also confirm the presence of this structure and moreover the right positioning of the fronts by the altimetry.

Figure3: Chlorophyll concentration (mg/m3) map (upper panel) and Sea Surface Temperature map (0.1 degrees Celsius) (bottom panel) over the Mediterranean Sea. The Absolute Dynamic Topography derived from the MSLA maps is superimposed with the black arrows.

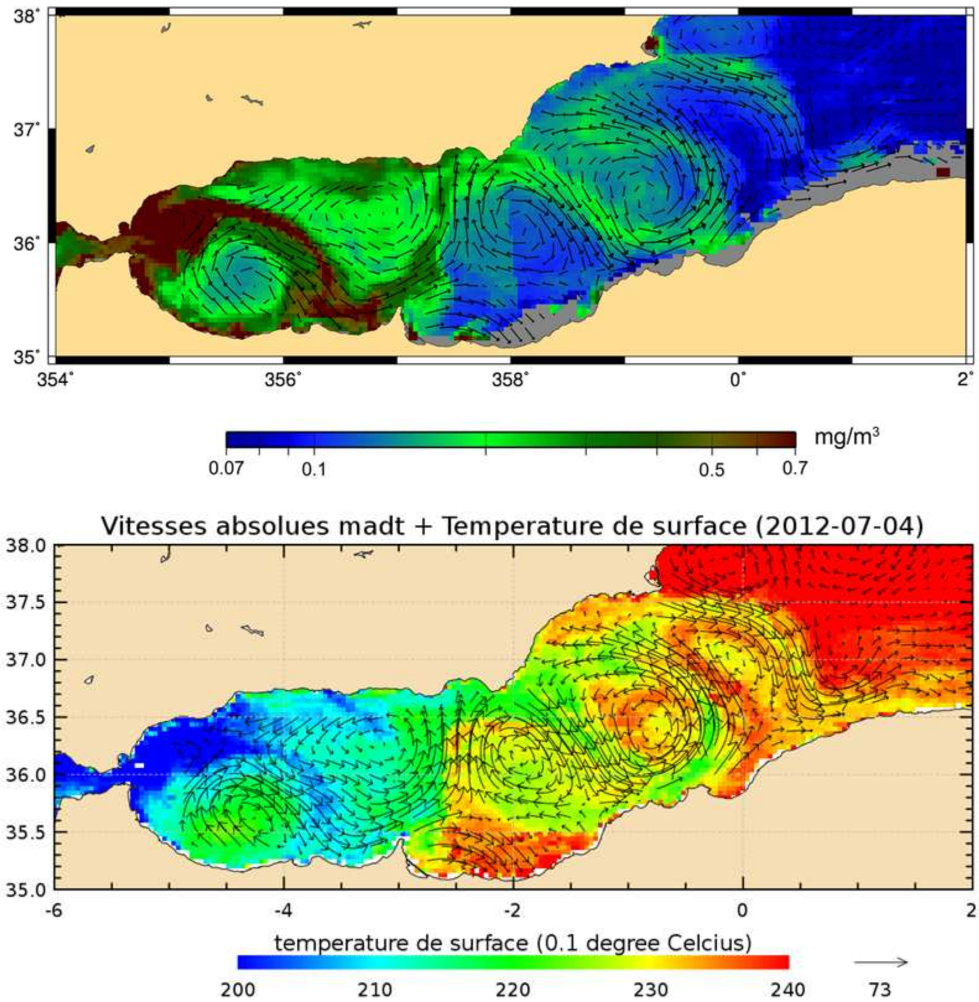


Figure 4 shows the Jason-2 and Cryosat-2 tracks that were used to derive the map over the area. The Cryosat-2 tracks fill the gaps in between the Jason-2 tracks, helping to better delineate the positive anomaly centered at longitude 0° and also detect the negative part of the anomaly a few kilometers westward which would have been missed without Cryosat-2 data.

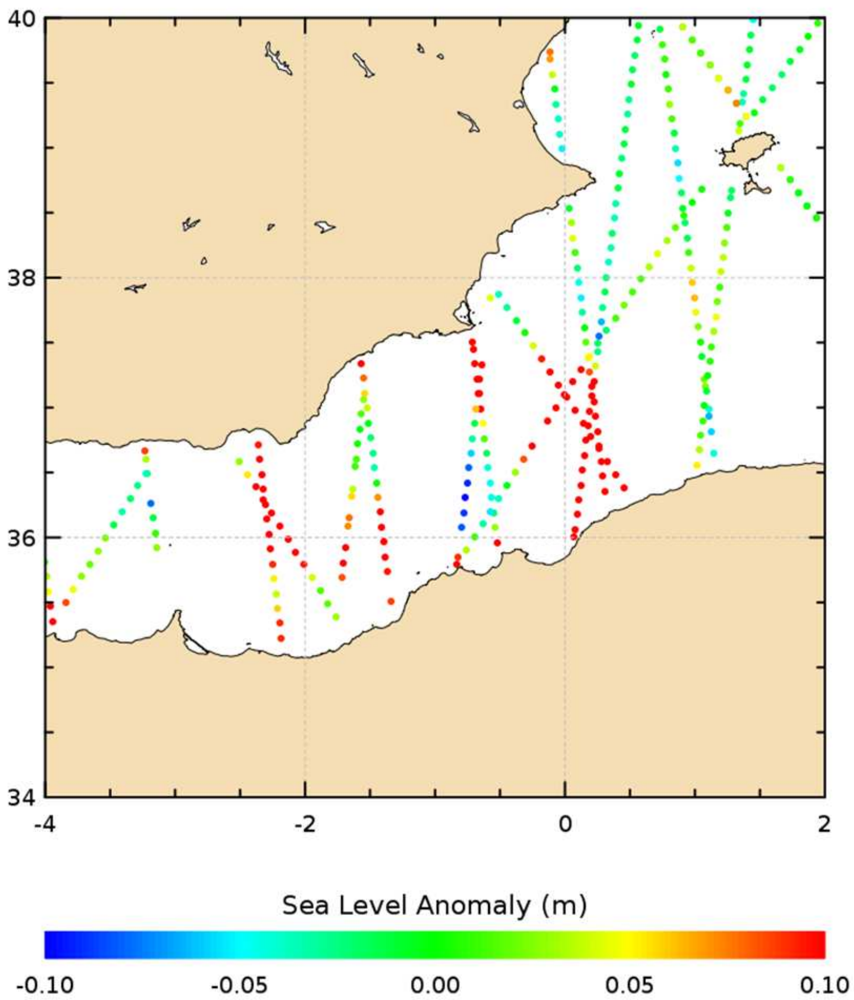


Figure 4: Along track SLA (m) for Jason-2 (slant tracks) and Cryosat-2 (vertical tracks) tracks in the Alboran Sea between June 27 and July 11 2012

Another example is found in the Black Sea with a different satellite configuration. Here we compare the Near Real Time map obtained with 3 satellites (Jason-2, Jason-1 and Envisat) with a four satellite map obtained when adding Cryosat-2 (Figure 5). This latter detects a positive anomaly between 41°N and 42°N, which was completely missed by the three sensors. The presence of this eddy is confirmed by the Sea Surface Temperature map obtained at the same date (Figure 6). Cryosat-2 observations add some precious information in the holes of the three satellite constellation, especially for the detection of small scale structures.

The future

As already mentioned, Cryosat-2 is the first altimeter that provides SAR mode measurements. This technique will be used for the coming Sentinel-3 mission scheduled in 2014, dedicated to topography measurements over ocean and ice surfaces. While there is a long experience of conventional pulse limited altimeters processing, SAR nadir looking data are new and need in depth validation. There is routine acquisition of SAR data over dedicated ocean areas, which are very useful to assess the quality of the SAR processing methods which are currently under development over ocean (Gommenginger et al, 2010, Boy et al 2012). Figure 7 shows the geographical mask of the different acquisition mode which is used since May 2012. The regions acquired in SAR mode are mainly located in the European seas, over the Agulhas Current and over a large zone in the equatorial Pacific which has been selected for a quality assessment of SAR processing algorithms (standard sea state conditions associated to low oceanic variability).

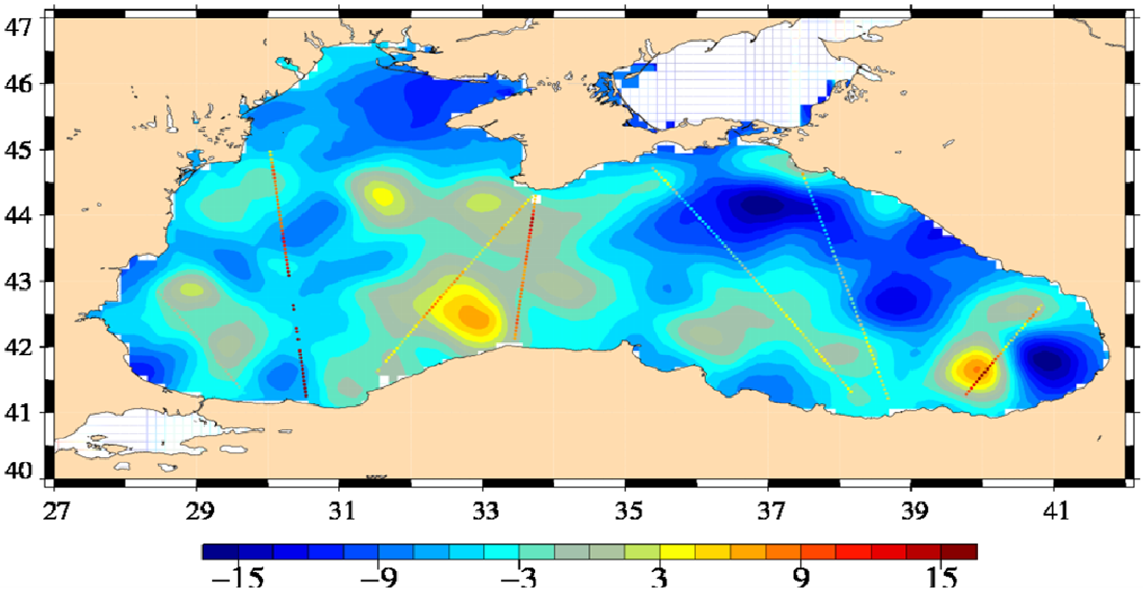


Figure 5: MSLA map (cm) obtained with 3 satellites (Jason-2, Jason-1 and ENVISAT on their repeat track orbit, upper panel) and 4 satellites (+Cryosat-2, bottom panel) over the Black Sea for a Near Real Time production. Along track SLA profiles for Cryosat-2 (vertical tracks) and Jason-2 (slant tracks) are super imposed. The tracks have been selected in a 2 day window from the map.

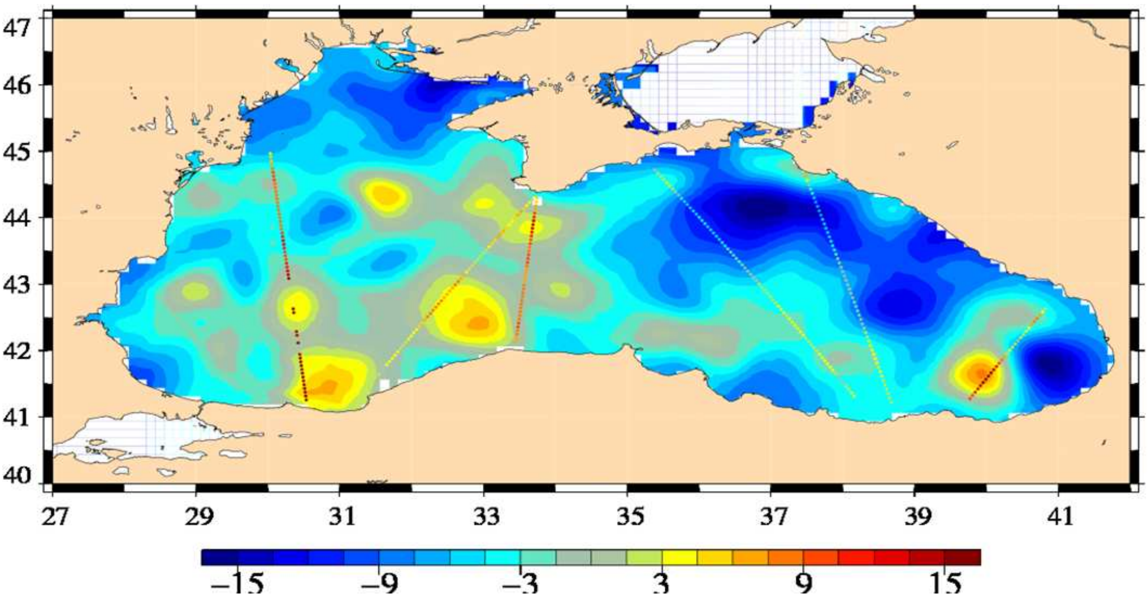
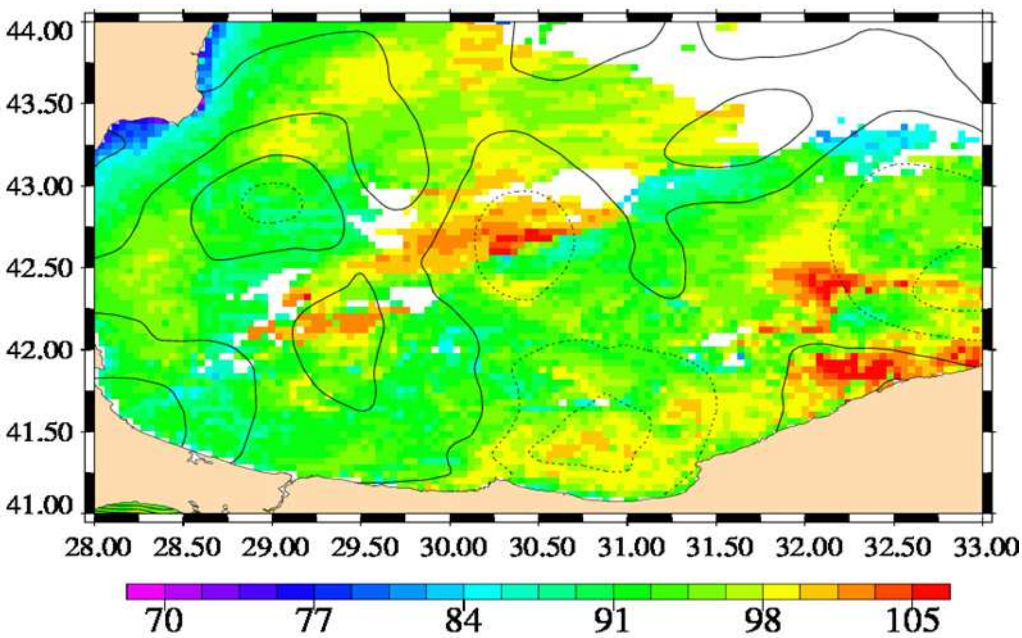


Figure 6: Sea Surface Temperature (0.1 degrees Celsius) map. Contours of MSLA (m) in black obtained with the 4 satellite configuration are super imposed



While dedicated SAR processing is not mature enough for operational oceanography, processing was developed by CNES in the CPP to perform a pulse limited like processing. It allows retrieving sea state and sea level as for conventional altimeters but at the price of a twice higher noise level. Thanks to this processing, all seas are covered with a seamless transition between LRM and SAR zones. Figure 8 exhibits the transition between LRM and SAR areas in the Agulhas Current. Despite the higher noise in the LRM like processing, oceanic structures are perfectly tracked. This allows getting a complete coverage of the oceans, especially over the European Seas.

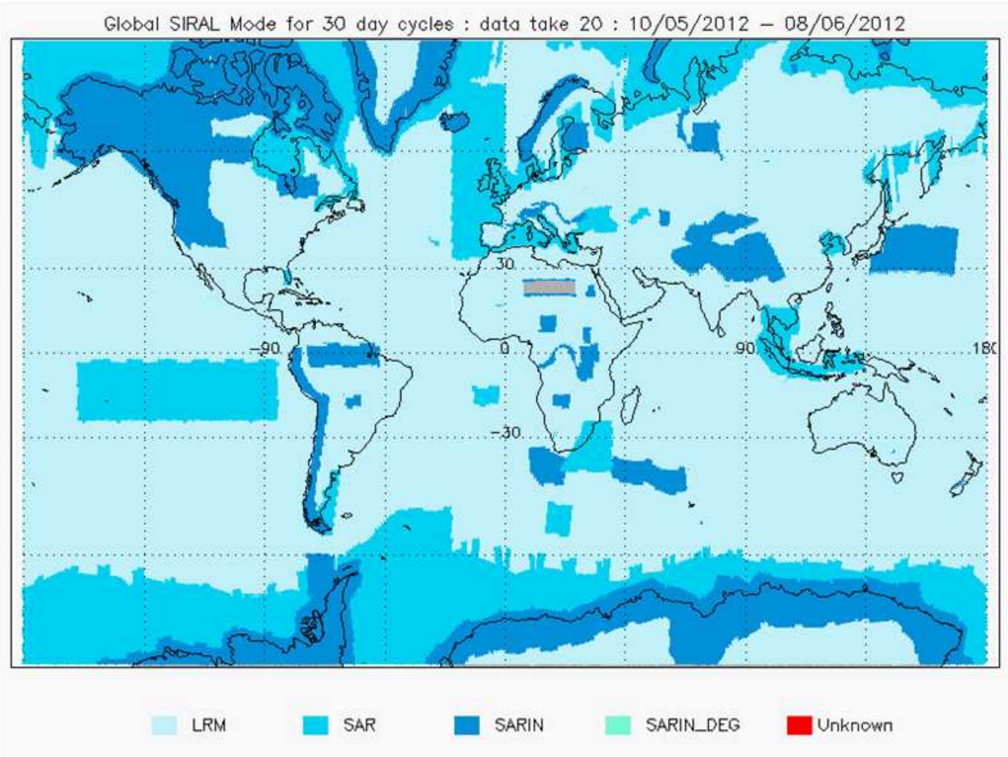


Figure 7: geographical mask of Cryosat-2 acquisitions. The altimeter is in LRM mode (light blue), in SAR mode (medium blue) and SARIn mode (dark blue)

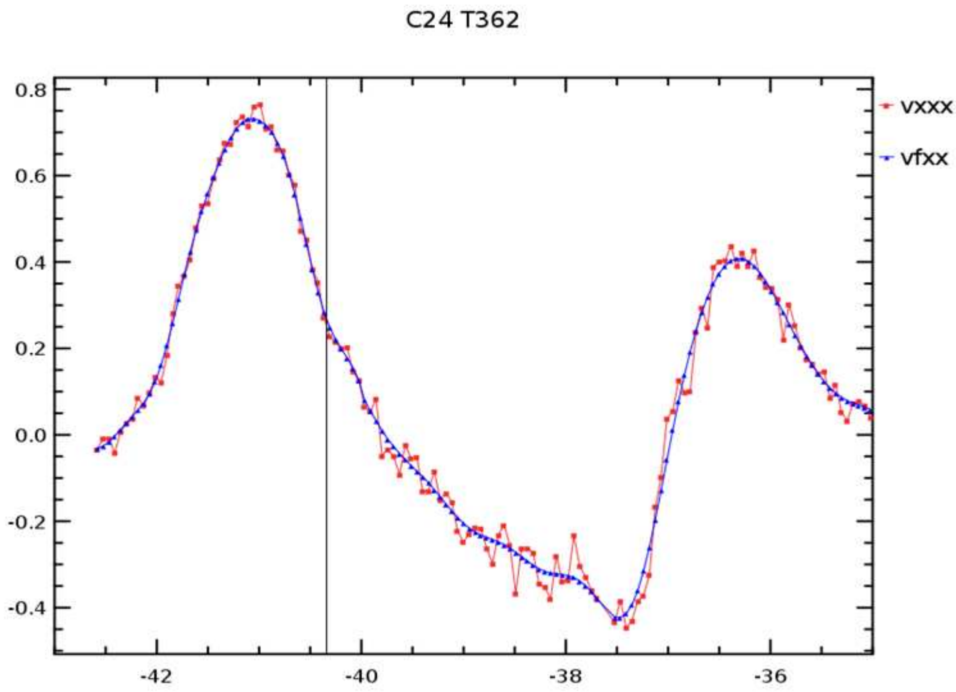


Figure 8: Along track SLA (m) for track 362 over the Agulhas region. The black line shows the latitude where the data are separated between LRM mode (south of 40S) and SAR mode (north of 40S) processed with a LRM like processing. 1 Hz data (red curve) shows a greater noise in the LRM like processing. Smoothed data (with a 50 km cut off frequency) are superimposed (blue curve)

In theory, the SAR mode allows to get sea level measurements with a lower noise and an improved along track spatial resolution (an along track resolution of 300 m compared to the standard altimeter footprint of 10 to 20 kilometers). First results appear very promising to reach smaller along track spatial scales. Figure 9 shows the energy spectrum of the sea level anomaly over the Equatorial Pacific obtained with SAR dedicated processing. The red spectrum perfectly follows the slope of the oceanic signal up to 50 km whereas it departures from the signal at 100 km with a conventional altimeter as Jason-2 (black curve). The lower spatial bound (where observation energy level represents twice the true signal level) is found at 30 km with SAR compared to 70 km with LRM altimetry. Finally the SAR data provide a noise level close to 5 cm at 20 Hz (the full altimetry resolution) compared to the 8 to 9 cm usually observed with LRM altimeters.

These first results over the Pacific confirm that the Cryosat-2 SAR data and the coming Sentinel-3 data will improve the along track resolution and push the spatial limit of altimetry down to 30 to 50 km scales, at least in the along track direction. This potential has to be confirmed over other regions where the spatial correlation scales of the signal are quite small (less than 100 km) and where such an improvement in the altimetry data is of great interest (Mediterranean Sea, Black Sea etc…).

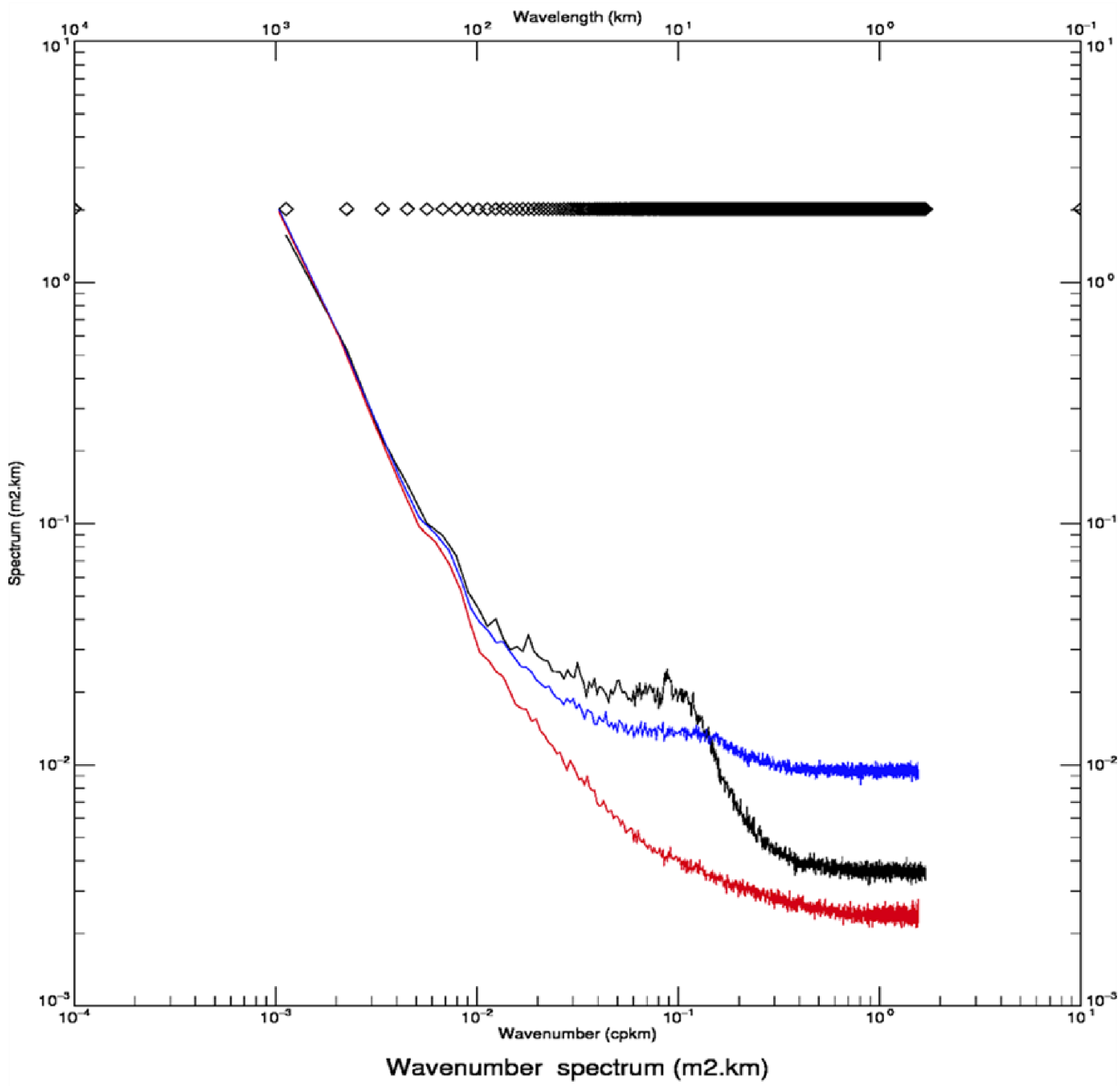


Figure 9: Mean PSD (Power Density Spectrum) of SLA for Jason-2 (black), Cryosat-2 with SAR processing (red) and Cryosat-2 with LRM like processing (blue) for the SAR region acquired over the Pacific.

Conclusion

Even if Cryosat-2 was designed for the cryosphere observation, it has the potential on the paper to serve oceanic needs, both for operational and scientific objectives. The capability to provide high quality data for oceanic studies and operational oceanography was fully demonstrated with several results presented here.

Thanks to space agencies efforts (CNES, ESA and NOAA), Cryosat-2 is now a major component of the operational altimetry constellation since February 2012 and will continue to bring a precious contribution in the coming years.

Furthermore, thanks to its innovative SAR technique, Cryosat-2 will provide new perspectives for altimetry, regarding the smallest spatial scales that are achievable with altimetry. The SAR technique is pushing down the limit of the spatial resolution of the altimetry by providing data of very high quality for mesoscale and sub mesoscale observation. Cryosat-2 mission is a precursor of Sentinel 3 mission that will continue to offer this capability in Copernicus (used to be called GMES) context.

Acknowledgements

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IMPACT OF THE LOSS/ADDITION OF SATELLITE ALTIMETRY ON MERCATOR OCEAN OPERATIONAL PRODUCTS

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Introduction

Real and delayed time ocean analysis and forecasting systems highly rely on SLA observations to constrain the ocean surface variability. The satellite constellation is evolving in time: the number and quality of satellite observations greatly changed over the last years. This paper addresses the impact of the change of the satellite constellation on Mercator Ocean analysis and forecasting systems. We first looked at the impact of the loss of the ENVISAT and Jason1 along track SLA data in the beginning of the year 2012 in the real time products. The following question then arises: how many satellites and at which precision do we need in order to keep the actual level of quality of our products? This is illustrated by a dedicated set of Observing System Experiments (OSEs). Preliminary results of such study are shown here. The need for a sustainable global ocean observing system is confirmed. Figure 1 shows the altimetry satellites available for a given period.

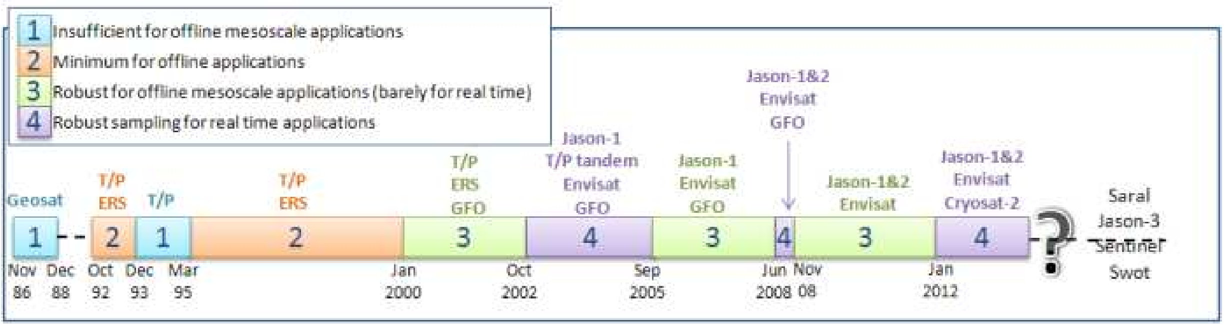

Figure 1 : Altimeter sampling related to applications. Credits CLS. (http://www.aviso.oceanobs.com/en/altimetry/multi-satellites.html)

Impact of the constellation changes on real time operational ocean analysis quality

The unavailability of Jason-1 during few weeks in early 2012 and the loss of Envisat in April 2012 have significantly reduced the SLA coverage for a short period of time in 2012(Figure 2). Cryosat-2 observations and Jason1 observations on its geodetic orbit have since been added in the Mercator Ocean assimilation systems. An extensive description of those systems is given in the article by Lellouche et al., 2013. The degradation of Mercator Ocean product quality during this period is estimated by looking at operational diagnostics covering several months before and after the loss of Envisat. Figure 3 shows the time evolution of the mean and RMS model observation misfit for SLA observations from December 2010 to May 2012. No significant changes in the error level can be seen in those diagnostics after the loss of Envisat and Jason 1.

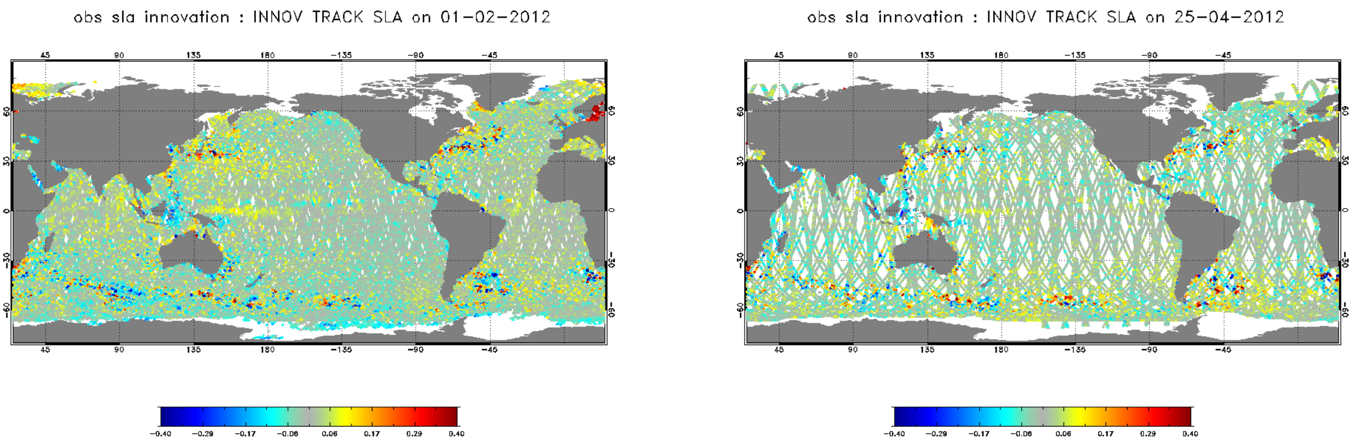

Figure 2: SLA innovations along tracks in centimeters, with Jason-1, Jason-2 and Envisat altimeters (left) in February 2012, and with the Jason-2 and Envisat (right) in april 2012.

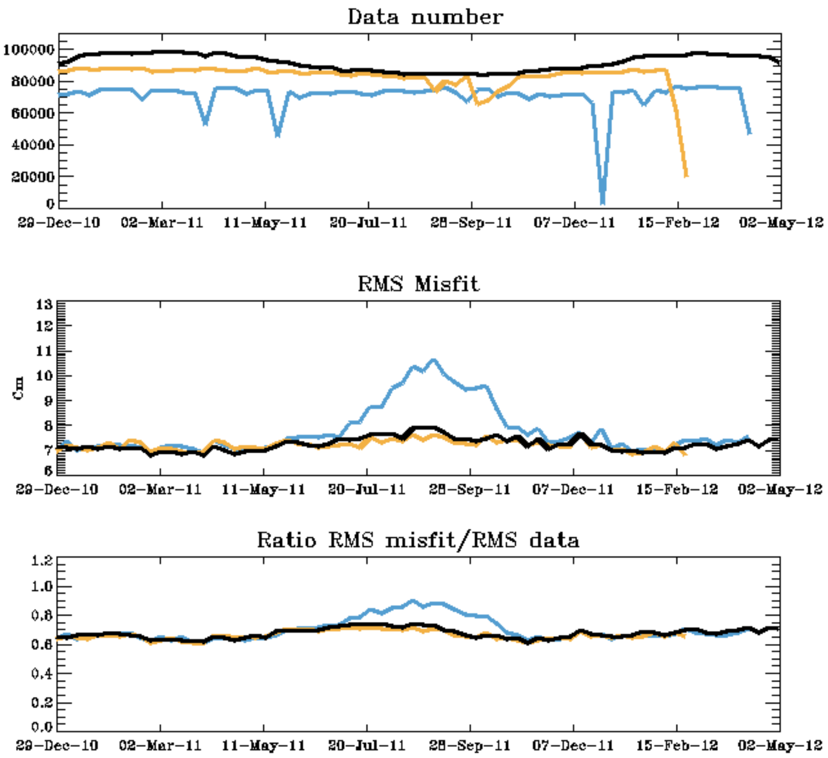

Figure 3: Global altimetry assimilation scores (orange: Jason-1, black: Jason-2, blue: Envisat) for PSY4V1R3. Upper panel: Number of assimilated SLA observations; Middle panel: RMS of the model observation misfit for the different altimeter missions in centimers; Down panel: RMS of the model observation misfit for the different altimeter missions in centimers weighted by the RMS of the observations.

Mean and RMS errors in salinity and temperature, as well as altimetry and SST assimilation scores did not exhibit any signal that could be for certain attributed to the lack of SLA measurements. An estimation of the intensity of the mesoscale activity did not display any slowing down and the mixed layer depth estimation did not show any clear degradation with respect to previous years (not shown). This illustrates the need of dedicated Observing System Experiments (OSE) to assess the impact of the number of altimeter data sources on the analysis and forecast system accuracy. In such studies, a simulation where all available observations are assimilated gives a reference to compare with other experiments where one or more data sources are not assimilated. Conclusions highly depend on the analysis system, the prescribed observation error level and scale and the model configuration and resolution.

OSEs with the Mercator systems

Impact experiments are performed with the global ¼° system (PSY3V3). Three simulations have been running over 4 weeks from August 11th to September 9th 2010 when three satellites are available. The only differences between those simulations are the number of assimilated satellites (see Table 1). In situ and SST observations are assimilated as usual. Model misfits to withheld SLA observations are still computed for diagnostic purposes. Along track AVISO/CLS Delayed Time SLA products are assimilated. The goal is to identify the changes in the analysis when one (Envisat) or two (Envisat and Jason-1) SLA data sets are removed.

	Jason 1	Jason 2	Envisat
Run 1	**x**	**x**	**x**
Run 2	**x**	**x**	**no**
Run 3	**no**	**x**	**no**

Table 1: SLA data sets assimilated in the different runs

We show differences in the analyzed model fields and diagnostics mainly performed in the observation space over the last week of the one-month experiments. These observations based diagnostics are considered as a good reference for analysis and forecast error estimation.
Differences in the ocean temperature estimations at 300 meters depth are presented in Figure 4. Changes from run 1 to run 2 (where Envisat is removed) are restricted to small scale structures located in regions of strong eddy activity: western boundary currents, circumpolar current, confluence zone and Agulhas region. There is no significant change in the tropics.
Changes from run 1 to run 3 (only Jason-2 is assimilated) are far stronger: the SSH differences reach at least 2 cm almost everywhere (not shown). At 300m temperature differences reach 0.5 to 1°C locally. For our experiment and in our configuration, we can already establish that there is a great qualitative drop when we decrease the number of SLA sources from 2 to 1, much larger than from 3 to 2.

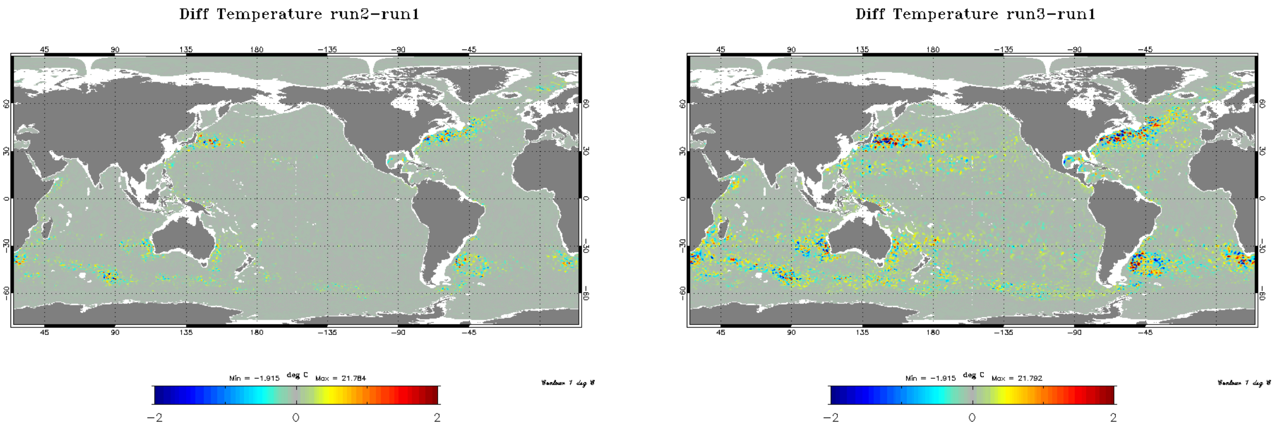

Figure 4: Temperature difference in °C at 300 m depth between run2 and run1 (left) and between run3 and run1 (right) on September 2nd, 2010.

We now look at the misfits between observations and their model counterparts, in the three runs. The differences should be within the prescribed error bar to consider the assimilation process as successful for a given data set. SLA and in *situ* salinity and temperature profile model-observation misfits have been computed.

Comparisons with the in situ temperature and salinity profile observations can help to measure whether the changes occurring when there are 1, 2 or 3 SLA data sets assimilated are realistic or not. In global mean and in most of the regions, the impact is weak but it is visible and tends to deteriorate when one satellite is assimilated instead of three (not shown). Consequences can be seen at different depth for both temperature and salinity: thanks to the multivariate assimilation scheme, the SSH observation information is projected onto the T and S 3D fields.

For SLA misfit statistics, the transition from 3 to 1 SLA source causes a degradation of the system performance. This is illustrated by the RMS SLA model-observation misfits to the different satellites for the different runs in figure 5. The spatial array of SLA tracks from Jason 1 and 2 seems to efficiently control the model solution, except in regions where eddies dominate the ocean dynamics. Small scale structure estimation requires a dense observation array to be estimated and specific tuning of the assimilation scheme.

From previous experiments, it was shown that at least 3-month simulations are required to stabilize the error level. It probably corresponds to the loss of memory of the ocean initial conditions.

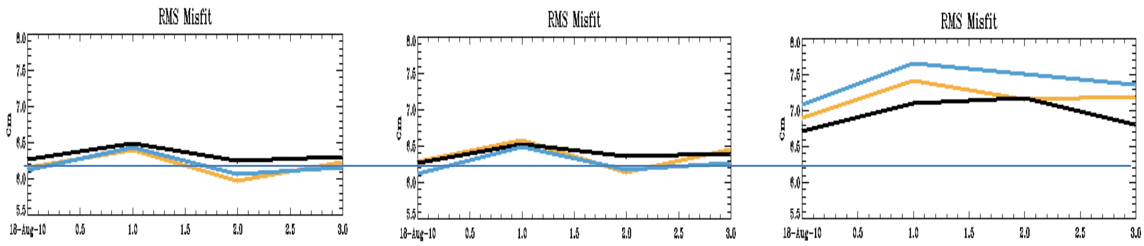

Figure 5: RMS misfit in centimeters to SLA observations over a month period with weekly analysis: Envisat in yellow, Jason2 in black and Jason1 in blue. Left: Jason 1, Jason 2 and Envisat SLA assimilated (run1), middle panel:Jason 1 and 2 (run2) , right panel: Jason 2 (run3).

Conclusions

From the experiments shown here, we conclude that constraining the global ¼° Mercator system PSY3V3 with 2 satellites instead of 3 does not lead to large changes. It should be recalled that the “third” satellite, Envisat, has an instrumental error with an amplitude twice larger than the others. The impact of the removal of Envisat is visible only in regions dominated by a strong eddy activity: small scale structures require denser observation coverage to be properly estimated. The combination of Jason 1 and 2 seems in fact to be optimal in the context of the PSY3 system. This can be due to the fact that the number of “efficient observations” is reached for a given analysis location. With only one satellite like Jason 2, the overall quality of the analysis is clearly degraded and even the SLA misfit to the remaining altimeter becomes larger than the prescribed error. The system lost its equilibrium.

Those results cannot be extended to the Cryosat satellite which has a very different “groundprint” leaving large regions free of data, more precisely larger than the model scale and analysis scale. Future work includes more specific diagnostics not only based on statistics but also on spatial structure identification (fronts, filaments), mixed layer depth characteristics, spectral analysis... Such experiments should also be done at 1/12°spatial resolution.

All the studies presented here are based on assimilation of SLA data in a numerical model in addition to other data sets. The results differ from the impact studies in the context of 2D mapping of SLA (by Pujol et al, 2012) where large errors were diagnosed following the loss of Envisat. The Mercator Ocean global analysis system benefits from other information source that are the model forecast, in situ temperature and salinity profiles, SST data and the 2 Jason satellites which tracks are complementary and offer a homogeneous coverage. The dynamical model brings useful information, and ensures spatio-temporal continuity when 2 satellites like Jason1 and 2 are available. This does not demonstrate yet that more than 3 satellites are needed to obtain accurate results, at least in the ¼° system PSY3, but it can be inferred from earlier results with the 1/12°Atlantic system (PSY2) that 3 or more satellites are indeed necessary to obtain the nominal level of surface accuracy (SLA, currents, possibly MLD) in high resolution system (Benkiran, 2008). When only one satellite constrains the systems PSY3 or PSY2, the equilibrium of the entire system is lost. The prescribed error levels are currently under evaluation as some recent diagnostics (Desroziers, 2005) show that more information could be derived from the same number of observations in some regions and the prescribed observation error variance can be lowered. As the spatial resolution and accuracy of SLA products improve, our systems need to evolve to be able to benefit from smaller scale information contained in the along track SLA observations.

The observation array is constantly evolving and also the assimilation system. We plan to run Near Real Time OSE experiments within the GODAE Oceanview (http://www.godae.org/OSSE-OSE-home.html). Each month a given data set will be withheld and the simulation compared to the real time analysis and forecast. Diagnostics will be also developed to monitor the observation impact on real time production. Dedicated experiments will be conducted to help designing future observation system.

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EVALUATION EXPERIMENT TO TEST THE VALUE OF ALTIMETRY IN FOAM

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Abstract

A parallel version of the FOAM operational system was run, during April 2011, withholding Jason-2 altimeter observations in order to assess the impact of these data on the system. At the time Jason-1 and ENVISAT altimeters were also observing the ocean so withholding Jason-2 removed 43% of the altimeter data. Withholding Jason-2 data results in a 4% increase in the RMS SSH observation-minus-background differences. We also saw impacts on other model variables; around ±2ºC small scale changes in 100m temperature and around ±0.2 psu changes in surface salinity. The following month, May 2011, another parallel run of FOAM withheld all altimeter observations. Withholding all altimeter data led to a 16% increase of the RMS SSH observation-minus-background error. There were differences of at least ±2ºC in 100m temperature and at least ±0.2 psu in surface salinity and both were noticeably more widespread than those seen when only Jason-2 was withheld.

Introduction

As part of GODAE OceanView we have performed a number of Observing System Experiments (OSEs) to assess the impact of the observing network on FOAM the Met Office's ocean assimilation and forecasting system. An OSE involves running a copy of an existing assimilation run where some observations are excluded. The difference between this run and the original run assimilating all the observations allows a detailed assessment of the impact the observations have on the assimilation system.

GODAE OceanView is the follow on to GODAE (Global Ocean Data Assimilation Experiment) (Smith and Lefebvre 1997; Bell et al. 2010) which was an international group focussed on the development of operational ocean analysis and forecasting systems. Many members of GODAE now have operational ocean analysis and forecasting systems. The follow on, GODAE OceanView, is therefore directed at sustaining and developing the systems including the vital ocean observing systems required for operational ocean analyses and forecasts. The OSEs form a part of this effort in allowing us to demonstrate the value of the existing observing network to our ocean forecasting systems. The Met Office took the lead in running a whole series of Near Real Time (NRT) OSEs reported in Lea (2012). Here we focus on the altimeter OSE results in detail. A system description follows. The results of an OSE where Jason-2 data is removed are followed by the results of an all altimeter data OSE. Finally, the results are discussed in the conclusion.

System Description/ Method

FOAM (Forecasting Ocean Assimilation Model) is the Met Office's short range (0 to 6 day) operational open ocean forecasting system (Storkey et. al. 2010). Remotely sensed satellite L2p SST (sea surface temperature) and in-situ SST data, profile temperature and salinity data, SLA (sea level anomaly) altimeter data and sea ice concentration data are assimilated in the NEMO (Nucleus for European Modelling of the Ocean) model using the analysis correction assimilation scheme. Note, the operational system has been upgraded since these experiments to use NEMOVAR, a 3D-Var scheme. Data is assimilated into a global model at ¼º resolution and various nested models at 1/12º. The experiments below use only the global model. The operational system runs back 48 hours each day and assimilates all the available data in two 24 hour periods (day minus 2 and day minus 1). Running from day minus 2 means that data that arrive late can be used to improve the results.

In this study we perform two OSEs (Observing System Evaluations); running an identical copy of the operational system global model with the same forcing and observations, with Jason-2 or all altimeter observations excluded. We compare the results with the system assimilating all the data in order to assess the impact of the data excluded. The "no Jason-2" experiment was run for all of April 2011 starting from the same initial model fields as the operational run but then allowing the experiment to evolve separately during that time. The "no altimeter" experiment was run for all of May 2011, again, starting from the operational model fields, but then allowed to evolve separately. Direct comparison of the Jason-2, and all altimeter impact would be easier if the same month was run, but this was intended to be a demonstration of NRT running and it was considered too expensive to run two copies of the FOAM system in parallel with the operational suite.

It is important to note that FOAM altimeter data is multi-mission data, sourced through AVISO, where Jason-2 data is used to correct the other altimeter data using the track crossovers. This means that the OSE is not a full test of the loss of Jason-2 since its impact is still felt through the corrections of Jason-1 and ENVISAT altimeter data.

Results of excluding the Jason-2 altimeter data

In April 2011 there were a total of 1134330 along track altimeter observations of which 495429 (43%) were Jason-2 observations. The impact of excluding Jason-2 data on global observation-minus-background (innovation) statistics is shown in Table 1. There is a small increase in the RMS innovations for all observation types. In-situ SST (2.7% increase), AATSR SST (1.3%), SSH (3.9%), profile temperature (1.6%) and profile salinity (2.4%). This suggests some complementarity in the data with altimeter data helping to improve the model forecast of other quantities even though those other data also being assimilated. For example, having eddies in the right place helps to improve the fit to SST data.

	Operational	No Jason-2 altimeter	RMS change
SST in-situ / ºC	0.594 (-0.105)	0.610 (-0.109)	+2.7%
SST AATSR / ºC	0.480 (-0.016)	0.486 (-0.017)	+1.3%
SSH / m	0.073 (-0.002)	0.076 (-0.002)	+4.1%
Profile T / ºC	0.575 (-0.011)	0.584 (-0.013)	+1.6%
Profile S / psu	0.125 (0.002)	0.128 (0.002)	+2.4%
Sea ice concentration	0.040 (-0.001)	0.040 (-0.001)	0.0%

Table 1. Global summary of observation minus background statistics, RMS (and mean in brackets) for different observation types accumulated globally over April 2011. For both runs we are comparing to all observations including all altimeter data.

A time series of the SSH observation-minus-background shows that removing the Jason-2 data takes some time to show its full impact (Fig 1). This partly results from the 10 day repeat cycle meaning that the direct impact is only observed at the next 10 day repeat. However, as the “No Jason-2” run is still drifting after 10 days, the model appears to retain information from previous cycles. Recall that both the operational and OSE run start with the same initial conditions which are from the FOAM operational system which has been assimilating altimeter data continuously for some years.

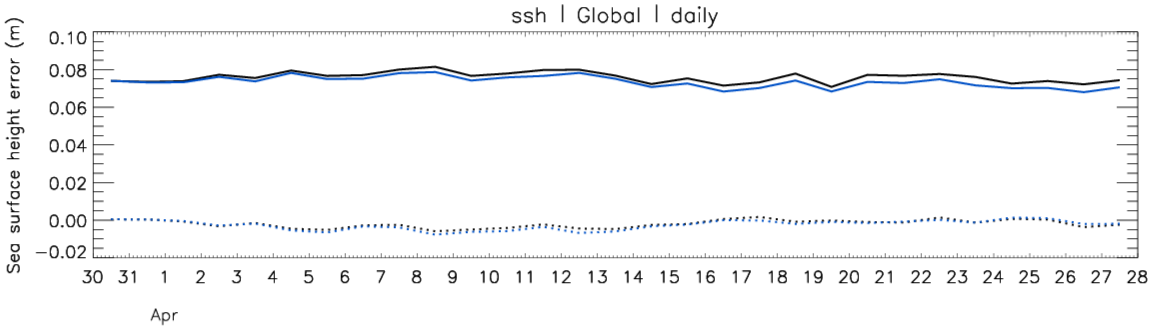

Figure 1. Observation minus background timeseries statistics. The black lines show results of the no Jason-2 run and the blue of the operational run. RMS errors plotted as solid lines and mean errors are plotted as dotted lines.

The observation-minus-background statistics of temperature as a function of depth (Fig 2) show the impact of the Jason-2 data is concentrated in the sub-surface. There is apparently only a rather small impact on salinity, however. In FOAM, altimeter assimilation uses the Cooper and Haines (1996) scheme to convert SSH increments into temperature and salinity increments. The scheme tends to produce the biggest increments near the thermocline or halocline.

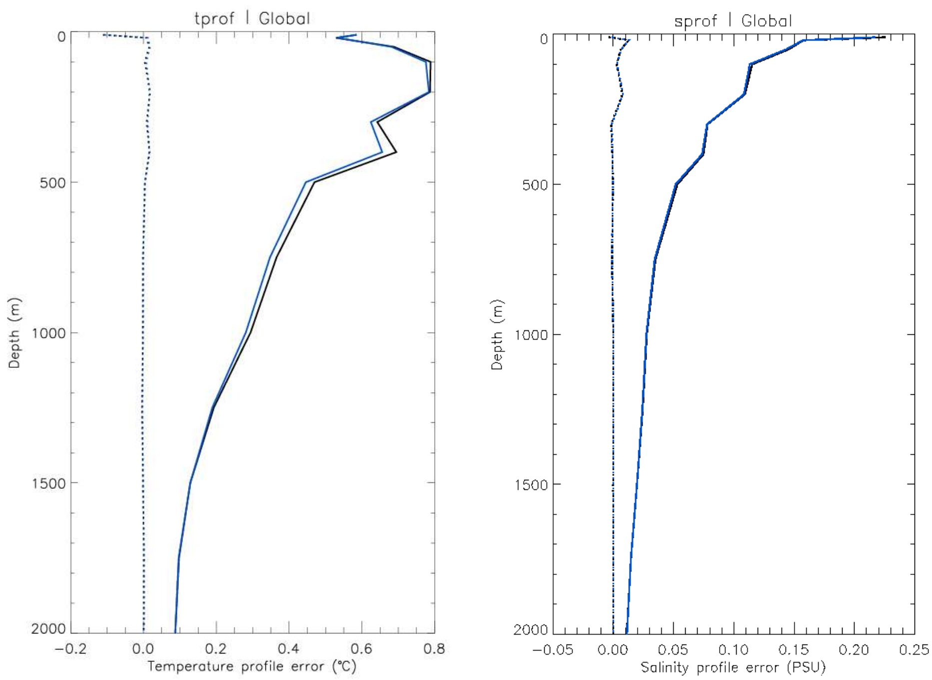

Figure 2. Observation minus background statistics for (a) temperature profile and (b) salinity profile data. The black lines show results for the no Jason-2 run and the blue for the operational run. RMS errors as a function of depth are plotted as solid lines and mean errors are plotted as dotted lines.

The model field differences of SSH at the end of the OSE period (Fig 3) show significant small scale impacts when Jason-2 data are not assimilated. These differences are greatest in the regions with strong mesoscale variability, for example the Gulf Stream, Kuroshio and Antarctic Circumpolar Current. The lack of impact at high latitudes is a consequence of the weak stratification. In regions where the top to bottom temperature gradient is less than 5ºC no Cooper & Haines increments are applied. Only large scale (~400 km) barotropic SSH increments are applied in these weakly stratified regions. Because the barotropic SSH increments are large scale it appears that removing one altimeter has very little impact.

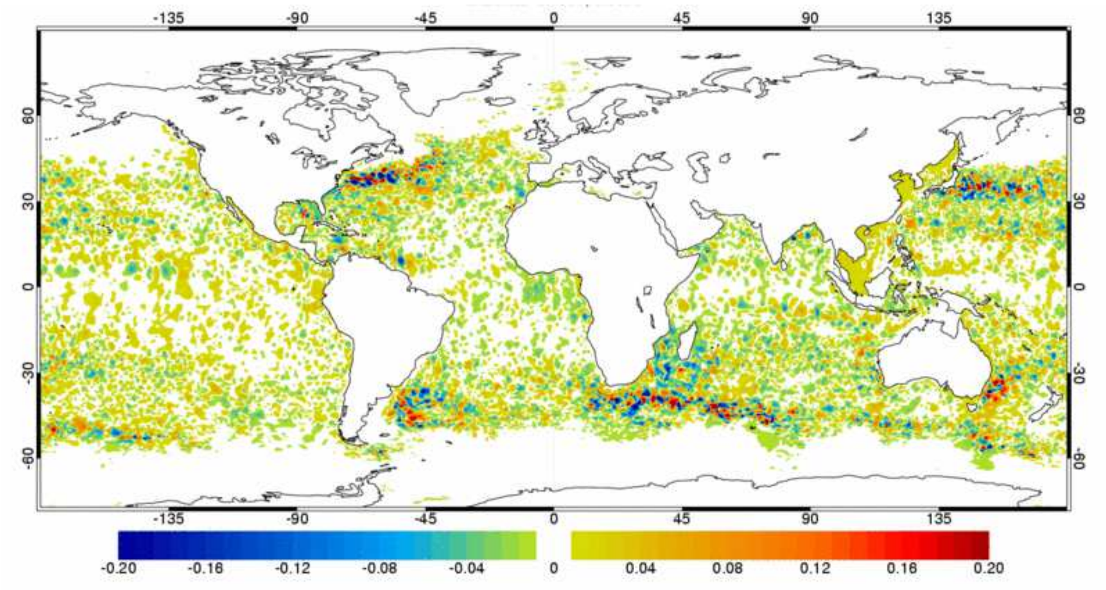

Figure 3. Map of the SSH difference (Operational minus "No Jason-2") in m. Derived from daily average fields at the end of Jason-2 OSE period.

The impact of Jason-2 is also strongly evident in the 100m temperature (Fig 4). There are large ±2ºC mesoscale differences particularly in regions of strong mesoscale variability coincident with the large SSH differences. However, there are also large temperature differences in the equatorial regions even though the SSH signal is quite weak, presumably a consequence of the strong vertical gradient in temperature. If we examine the surface temperature differences (not shown) we find they are quite small, this is because surface temperature is well constrained by the assimilation of the abundant sea surface temperature data.

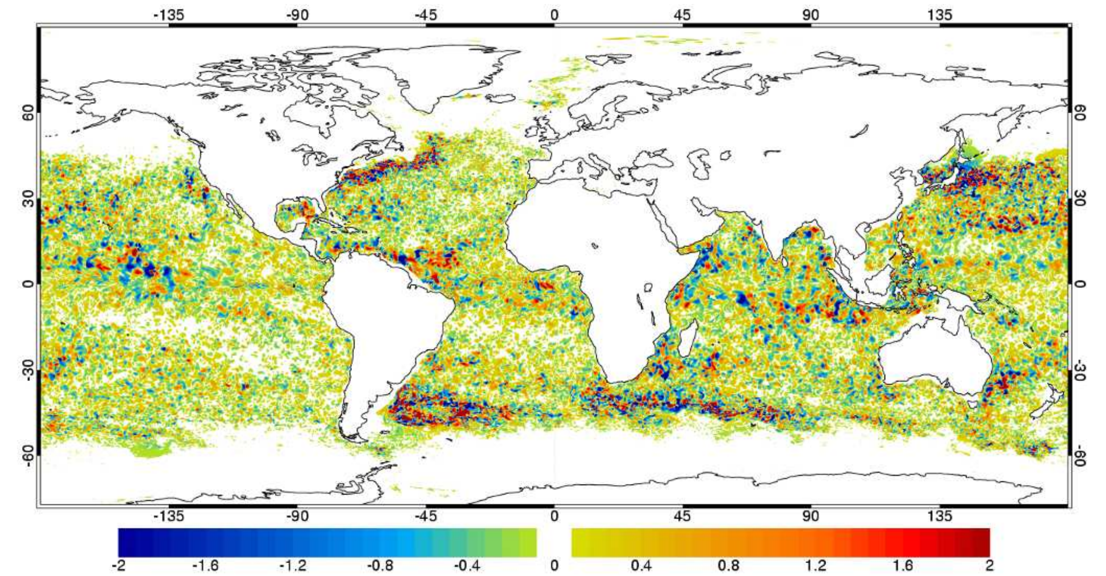

Figure 4. Map of the temperature difference (Operational minus "No Jason-2") in ºC at 100m. Derived from daily average fields at the end of Jason-2 OSE period.

In contrast to surface temperature there is a strong impact on surface salinity from Jason-2 (Fig 5). The regions with large salinity changes generally correspond well with regions of largest temperature impact (Fig 4). In some regions with large spatial variability in surface salinity, for example the Bay of Bengal, the salinity impact is exaggerated.

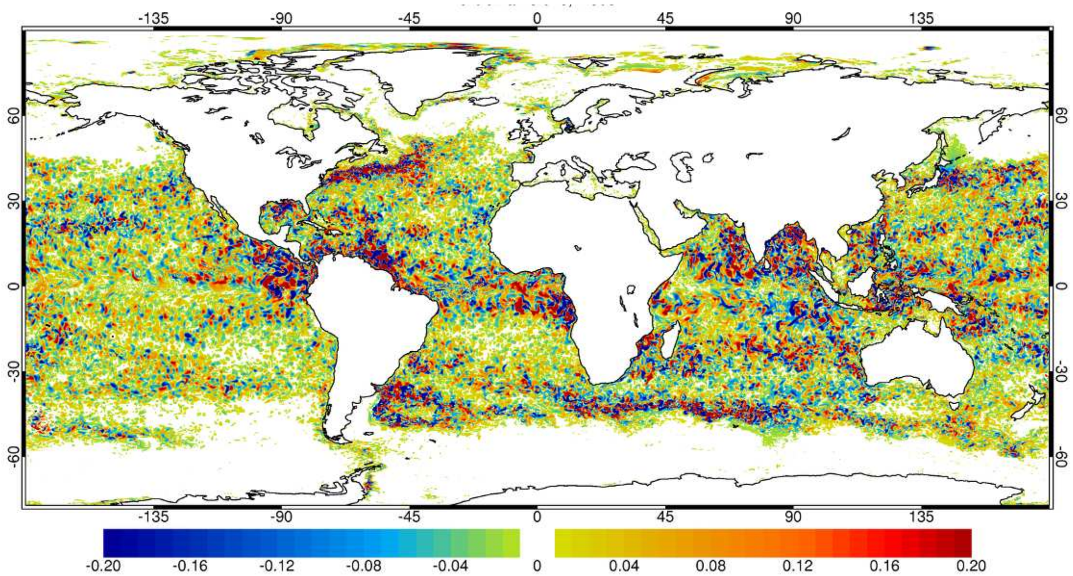

Figure 5. Map of the salinity difference (Operational minus "No Jason-2") in psu at the surface. Derived from daily average fields at the end of Jason-2 OSE period.

The effect of removing Jason-2 altimeter data can also be seen in the comparison of the two runs' velocities to that derived from drifter observations. The drifters are drogued at 15m depth. The model daily mean currents at 15m depth are compared to a velocity calculated from the drifter positions over that day (as in Blockley et al 2012). A number of QC checks are performed and any drifters which are known to have lost their drogue are excluded from the comparison. Table 2 shows the statistics of the model and observed velocity. The RMS error increases by 3% and 2% for the zonal and meridional velocity components, respectively. Time-series plots (not shown) indicate that the error increases in time so the statistics probably underestimate the ultimate impact of not assimilating Jason 2 data.

	Operational	No Jason 2 altimeter
Zonal velocity (ms^{-1})	0.222 (-0.009)	0.228 (-0.010)
Meridional velocity (ms^{-1})	0.201 (-0.002)	0.206 (-0.002)

Table 2. Global summary of drifter velocity observation minus background statistics, RMS (and mean in brackets) for the u and v velocity component accumulated globally over April 2011.

Results of excluding all altimeter data

There were 1078113 along track altimeter observations available in May 2011. All are excluded in the "no altimeter" run. The impact of excluding all altimeter data on global observation-minus-background statistics is shown in Table 3. There is a 16% increase in the RMS SSH error from 7.4 cm to 8.6 cm and an increase in bias of 2 cm averaged over 1 month. The in-situ SST, AATSR SST, profile temperature and salinity suffer from somewhat increased RMS by 1.9%, 1.9%, 1.3% and 0.8%, respectively.

	Operational	No Altimeter	RMS change
SST in-situ / ºC	0.628 (-0.117)	0.640 (-0.111)	+1.9%
SST AATSR / ºC	0.472 (-0.001)	0.481 (0.002)	+1.9%
SSH / m	0.074 (-0.002)	0.086 (-0.018)	+16.2%
Profile T / ºC	0.606 (-0.017)	0.614 (-0.017)	+1.3%
Profile S / psu	0.128 (-0.000)	0.129 (-0.000)	+0.8%
Sea ice concentration	0.043 (0.001)	0.043 (0.001)	0.0%

Table 3. Summary observation minus background statistics, RMS (and mean in brackets) for different observation types accumulated globally over May 2011. For both runs we are comparing to all observations including all altimeter data.

In the previous month we tested excluding Jason-2. If we compare the results, it is interesting to note that the increase in the RMS for temperature and salinity observations was somewhat higher even though we were still assimilating the other altimeters. While we are not comparing the same month, this indicates that the other altimeters were not as beneficial to FOAM as Jason-2. Indeed, after the OSEs were run we discovered there was a problem in the upstream processing of altimeter data (from AVISO) which resulted in excessive small scale filtering of real time Jason-1 and Envisat altimeter in FOAM. The problem did not affect the Jason-2 data. This may explain the results seen here, but the only way to confirm is to do new OSEs with more recent (fixed) data.

A timeseries of the SSH observation-minus-background RMS and mean errors in Fig 6 shows a steady increase in the RMS and a steady decrease in the mean of the "No Altimeter" OSE. The largest part of the RMS increase comes from an increase in the standard deviation. The increasing bias is caused by the FOAM global model having a freshwater imbalance because evaporation, precipitation and river inflow are not exactly balanced, something that is difficult to achieve in a real-time operational system. Without any altimeter assimilation to correct the model mean free surface height it rises by around 3 cm over the month.

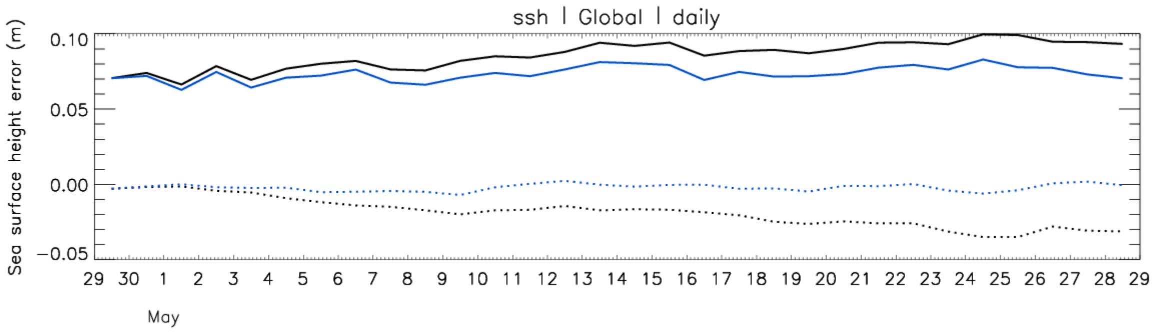

Figure 6. Observation minus background timeseries statistics. The black lines show results of the no altimeter run and the blue of the operational run. RMS errors are plotted as solid lines and mean errors are plotted as dotted lines.

The observation-minus-background temperature as a function of depth (Fig 7) shows a slight increase in RMS in the range of 0-200m. The increase is smaller than was seen in the Jason-2 OSE, probably for the reasons discussed above. An increase in salinity RMS occurs over a deeper range of levels 0-500m in this case more obvious than in the Jason-2 OSE.

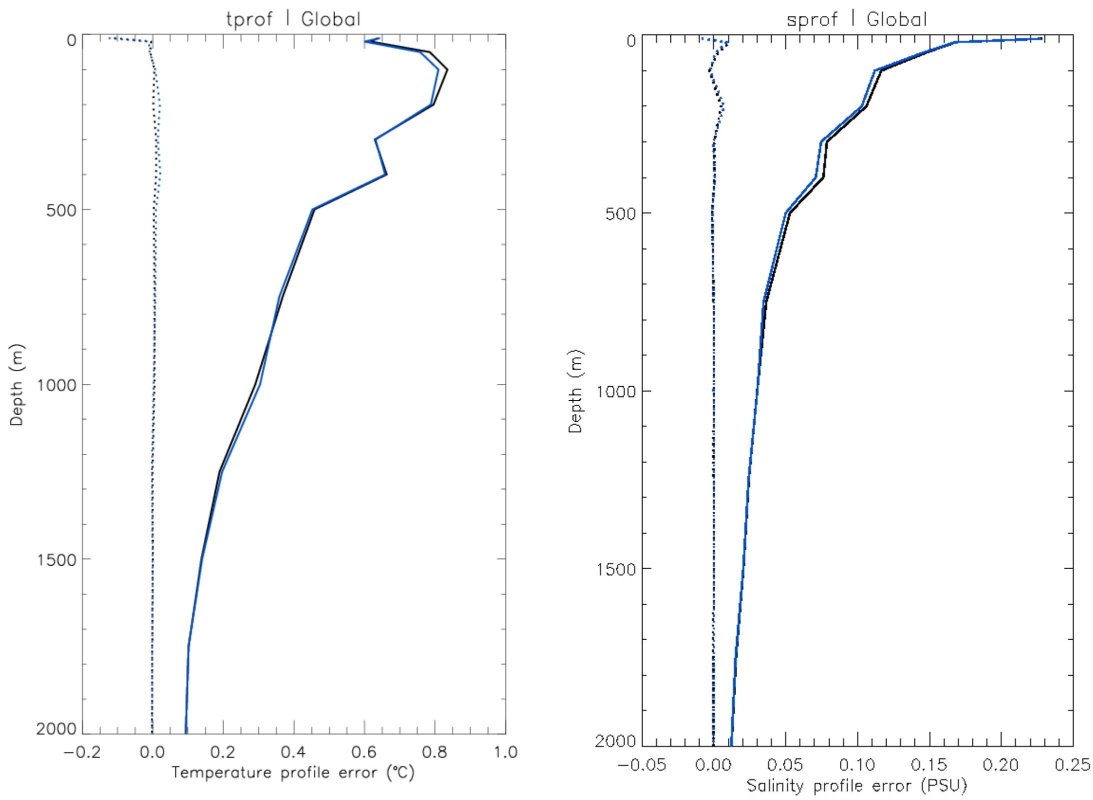

Figure 7. Observation minus background statistics for (a) temperature profile and (b) salinity profile data. The black lines show results for the no altimeter run and the blue for the operational run. RMS errors as a function of depth are plotted as solid lines and mean errors are plotted as dotted lines.

The drift in the model SSH is obvious in the difference plot of the model SSH at the end of the month between the operational and the no altimeter OSE (Fig 8). There are also very large (±20cm) differences in the mesoscale.

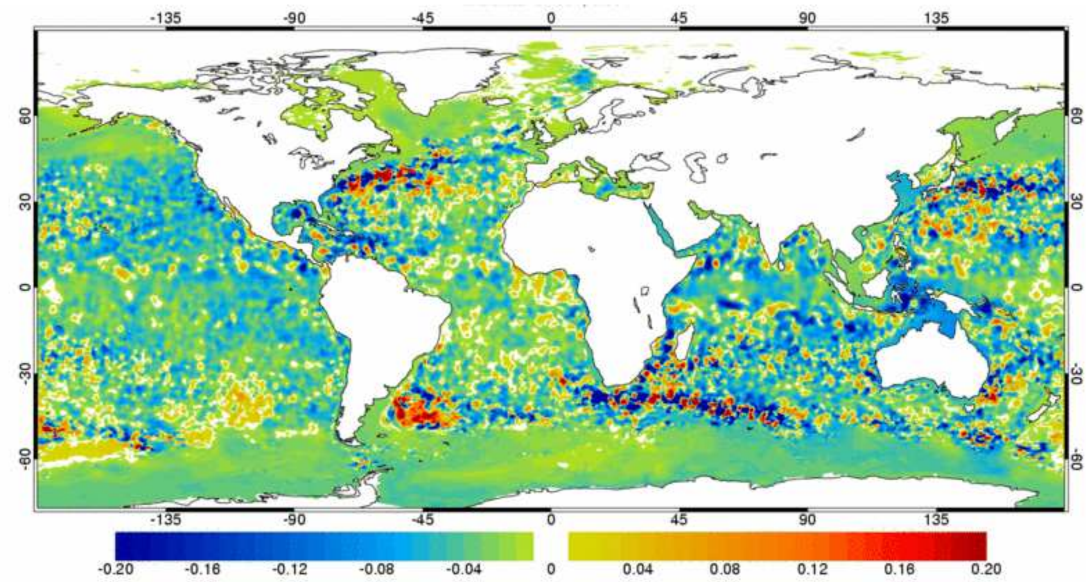

Figure 8. SSH difference (Operational minus "No altimeter") in m. Derived from daily average fields at the end of altimeter OSE period.

The impact of removing all altimeters is shown in a difference map of the 100m temperature (Fig 9). At least ±2ºC mesoscale differences are seen. These are significantly more widespread than the equivalent plot from the Jason-2 OSE. As with the Jason-2 OSE there are very large changes in the tropical temperatures despite the relatively small SSH signal in those regions, presumably a consequence of the strong vertical gradient in temperature. Again, if we examine the surface temperature differences (not shown) we find they are quite small, this is because surface temperature is well constrained by the assimilation of sea surface temperature data.

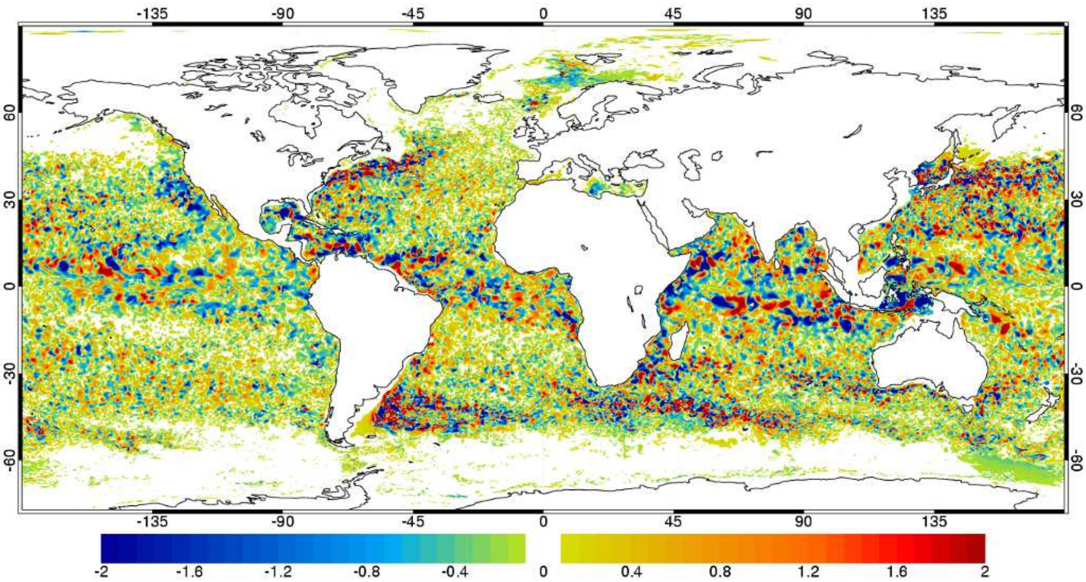

Figure 9. Temperature difference (Operational minus "No altimeter") in ºC at 100m. Derived from daily average fields at the end of altimeter OSE period.

As with the Jason-2 OSE, there is a strong impact on surface salinity from the altimeter data (Fig 10). One surprising result is the strong signal in the Arctic. It seems that at this time of the year, late northern spring, the ice is rather sensitive to small perturbations and any changes in the ice melt can result in large surface salinity changes.

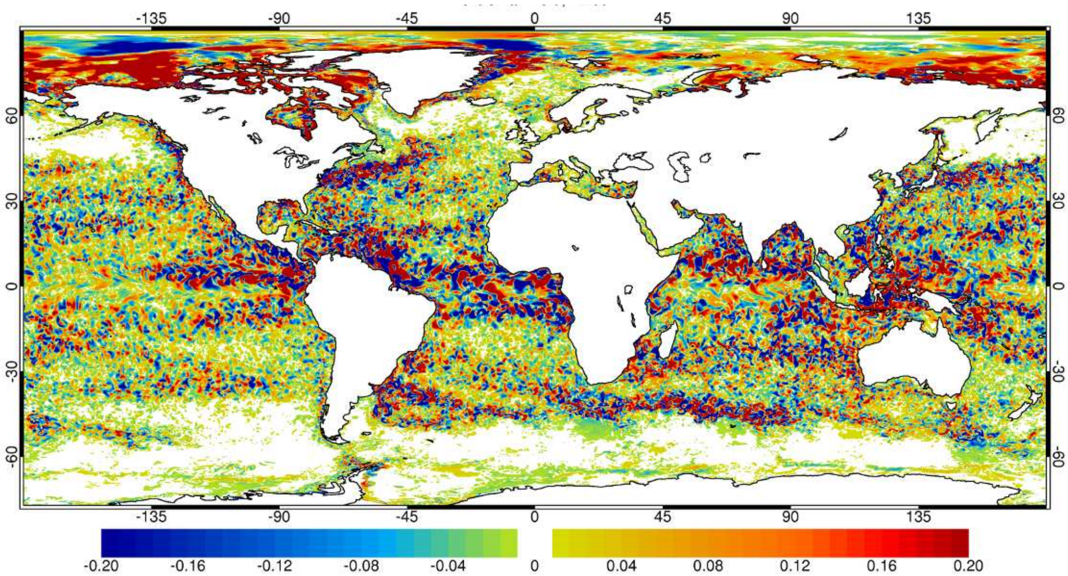

Figure 10. Salinity difference (Operational minus "No altimeter") in psu at the surface. Derived from daily average fields at the end of altimeter OSE period.

The effect of removing all altimeter data can also be seen in comparison of the two runs' velocities to those that are derived from drifter observations. Table 4 shows the statistics of the model and observed velocity. The RMS error increases by 3% for the zonal and meridional velocity components.

	Operational	No altimeter
Zonal velocity (ms^{-1})	0.225 (-0.004)	0.231 (-0.003)
Meridional velocity (ms^{-1})	0.209 (-0.000)	0.216 (-0.001)

Table 4. Global summary of drifter velocity observation minus background statistics, RMS (and mean in brackets) for the u and v velocity component accumulated globally over May 2011.

The degradation of the fit to drifter currents is roughly the same whether Jason-2 data are excluded or all data are excluded. Assuming there is nothing special about the months chosen this is consistent with the idea that Jason-2 was the most beneficial, at this time, of all the altimeters to FOAM.

Conclusions

Altimeter data has a strong impact on the mesoscale, in FOAM, unmatched by other data types. This is evident in the significant small scale changes in 3D model temperature and salinity. When altimeter data is excluded there is a degradation in the fit to the mesoscale dominated surface currents measured by drifters. Such an impact on the fit to surface currents is not seen with other observation types (Lea 2012).

While the impact on temperature and salinity of altimeter data is large it is less clear how much the altimeter data is actually improving the overall fit of the model to the true ocean 3D temperature and salinity. Comparison to real profile temperature and salinity data (mostly Argo) show only relatively small decreases in RMS error of around 3%. It may be that the real improvement is hidden because of the relatively sparse sampling particularly in the mesoscale dominated regions where altimeter assimilation may be expected to give the most improvements. The other possibility is that the results may also depend on the method of data assimilation. Other methods such as 4D-Var may be able to extract more accurate 3D temperature and salinity information from the altimeter data.

One weakness of this work is that many of the impacts of removing the data take some time to become fully evident. It may be useful, therefore, to perform longer OSEs in future in order to see the full impact of removing a particular data type. The problem is that each OSE requires a full run of the system and so is costly. In the future we may investigate other approaches which may be cheaper, for example calculating observation

sensitivities or observation information content (as in, for example, Chapnik et al. 2006).

The other important caveat is that the results are specific to the FOAM system. This issue is now being addressed as other GODAE partners begin to perform their own OSEs in near real time. This will allow much more robust and general statements to be made about the information content of altimetry and other observing systems.

Acknowledgements

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