Exploiting satellite altimetry in coastal ocean through the ALTICORE project

S. Lebedev,[1] A. Sirota,[1] D. Medvedev,[1] S. Khlebnikova,[1] S. Vignudelli,[2] H. M. Snaith,[3] P. Cipollini,[3] F. Venuti,[3] F. Lyard,[4] J. Bouffard,[4] J. F. Cretaux,[4] F. Birol,[4] L. Roblou,[5] A. Kostianoy,[6] A. Ginzburg,[6] N. Sheremet,[6] E. Kuzmina,[6] R. Mamedov,[7] K. Ismatova,[7] A. Alyev,[7] and B. Mustafayev[7]

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[1] Altimeter-derived information on sea level and sea state could be extremely important for resolving the complex dynamics of the coastal ocean. Satellite altimetry was not originally conceived with coastal ocean in mind, but future missions (AltiKa and CryoSat-2) promise much improved nearshore capabilities. A current priority is to analyze the existing, under-exploited, 15-year global archive of coastal altimeter data to draw recommendations for these missions. There are intrinsic difficulties in processing and interpretation of the data, e.g.: the proximity of land, control by the seabed, and rapid variations due to tides and atmospheric effects. But there are also unexploited possibilities, including higher along track data rates and multi-altimetry scenarios that need to be explored. There are also difficulties of accessing and manipulating data from multiple sources, many of which undergo regular revision and enhancement. In response to these needs, the ALTICORE (ALTImetry for COastal REgions – www.alticore.eu) project started in December 2006, funded for two-years by the European INTAS scheme (www.intas.be). The overall aim of ALTICORE is to build up capacity for provision of altimeter-based information in support of coastal ocean studies in some European Seas (Mediterranean, Black, Caspian, White and Barents). ALTICORE will also contribute to improved cooperation between Europe and Eastern countries and enhance networking of capacity in the area of satellite altimetry. This paper discusses the approach, summarizes the planned work and shows how the coastal community should eventually benefit from better access to improved altimeter-derived information. *INDEX TERMS:* 1240 Geodesy and Gravity: Satellite geodesy: results; 1241 Geodesy and Gravity: Satellite geodesy: technical issues; 1641 Global Change: Sea level change; 4217 Oceanography: General: Coastal processes; *KEYWORDS:* satellite altimetry, coastal ocean, ALTICORE project.

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[1]Geophysical Center, Russian Academy of Sciences, Moscow, Russia
[2]Consiglio Nazionale delle Ricerche, Istituto di Biofisica, Area Ricerca CNR San Cataldo, Pisa, Italy
[3]National Oceanography Centre, Southampton, UK
[4]Laboratoire d'Etudes Géophysique et Ocèanographie Spatiale, Toulouse Cedex 9, France
[5]Noveltis, Parc Technologique du Canal 2, Ramonville-Saint-Agne, France
[6]P. P. Shirshov Institute of Oceanology, Moscow, Russia
[7]Institute of Geography, Center for Caspian Sea Problems, Baku, Azerbaijan

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Introduction

[2] A number of studies [e.g., *Crout,* 1997] have provided a general understanding of the difficulties and challenges in interpreting altimeter-derived measurements in marginal seas such as those surrounding Europe; these studies have confirmed the great value of the altimetric products for large- and meso-scale applications. For instance, in the Mediterranean Sea, altimetry has been successfully applied at basin scale [e.g., *Ayoub et al.,* 1998; *Larnicol et al.,* 1995; *Vignudelli,* 1997] and in specific open sea regions [e.g., *Buongiorno Nardelli et al.,* 1999; *Vignudelli et al.,* 2000, 2003]. Comparison of satellite altimetry data with tide gauge data and hydrodynamic simulation results for the Barents

and White Seas [e.g., *Lebedev and Tikhonova,* 2002; *Lebedev et al.,* 2003] has shown that the remotely sensed data satisfactorily describe the hydrodynamic regime of these seas, including tides. Satellite altimetry data have allowed investigation of both mesoscale dynamics and water balances of the Black Sea [e.g., *Eremeev et al.,* 2004; *Ginzburg et al.,* 2003]. They are indispensable for investigation of significant seasonal and interannual variability of Caspian Sea level, including Kara Bogaz Gol Bay [e.g., *Lebedev and Kostianoy,* 2005]. The usefulness of standard altimetric products, however, is greatly reduced in coastal areas due to sampling issues, inaccurate corrections and other data quality problems [*Anzenhofer et al.,* 1999]. This has motivated recent investigations into ad-hoc data screening and processing to recover valuable information near the coast, which have yielded partial but encouraging results at a specific Mediterranean site [*Vignudelli et al.,* 2005].

[3] The coastal environment varies from the open sea in many ways. It is a region where sea conditions can vary quickly, both in time and space. Altimeter processing over these areas requires accurate knowledge of tides and of the hi-frequency atmospheric (wind and pressure) effects at the sea surface. Working next to land also poses the challenge of retrieving data flagged as unreliable but potentially recoverable after more careful, specific screening. There is clear scope for investigating the limitations of the current 1 Hz data stream and assessing the advantages and feasibility of the adoption of higher data stream rates (typically 10 Hz or 20 Hz). The standard data treatment also needs to be remodelled, minimizing the inclusion of spurious values and gaps and monitoring the processing chain from beginning to end. This need for better screening or interpolation/extrapolation of missing values does not only apply to the raw altimetric measurements, but also to the necessary corrections, that may suffer from similar (or worse) problems of land contamination and inadequate models. From a calibration and validation point of view, there is also the question of evaluating how improved averages over satellite footprints may be compared to point-wise values (in situ data) normally collected at different temporal scales; this involves non-trivial sampling and averaging issues, as well as assumptions on the local scales of variability of the altimeter-derived products.

Research Objectives and Strategy

[4] The central focus of the ALTICORE project is the improvement of the monitoring capabilities of satellite altimeters in the coastal region. The specific goals are:

[5] (1) to define the quality standards required for altimetry products in coastal regions based on the potential applications and user requirements;

[6] (2) to research new screening and processing strategies to recover data meeting the quality standards defined in (1);

[7] (3) to generate an improved altimetric data stream for the Mediterranean coastlines with these methods;

[8] (4) to carry out validation tests of the new product at a pilot and opportunity sites;

[9] (5) to apply the validated methodology to coastal areas in the Black, Caspian, White and Barents seas;

[10] (6) to setup a Grid-compliant system for data provision to modellers, forecasters and data-integrators in NIS countries;

[11] (7) to promote the added-value product amongst the user community.

[12] Altimetric missions in the last 15 years (TOPEX/Poseidon, ERS 1 and 2, GFO, Envisat and Jason 1) have resulted in great advance in marine research and operational oceanography, providing accurate sea level data (at cm error level) and high-value information products (including waves and wind) for fisheries planning, ship routing and offshore operations [*Cotton et al.,* 2004]. Satellite altimetry is now a mature technology and a routine component of operational earth observation systems. However, the utility of altimetric data near the coasts, where the impact on a number of economic activities could be significant, has been neither completely explored nor addressed from a user perspective. The main problem is that existing altimetric products are not optimised for coastal retrievals [*Vignudelli et al.,* 2000] owing to some processing and quality control issues, for instance the fidelity of corrective terms in coastal areas and possible contamination due to the presence of land in the footprint [*Lebedev and Kostianoy,* 2005]. These issues are currently impeding the effective use of altimeter-derived products in coastal areas [*Vignudelli et al.,* 2005]. This proposal aims at mitigating or removing, where possible, the obstacles to operational use of altimetry over coastal areas, with particular reference to the European seas (Mediterranean, Black, Caspian, White and Barents), through a concerted action of Western European and NIS Researchers in line with the framework of cooperation set by the INTAS initiative. We expect this project to advance coastal altimetry, from the present underexploited status, into pre-operational use with a fully implemented system for the production of quality controlled data and their dissemination, through a Grid-compliant interface, to the end-users. This will impact significantly on the use of altimetry for coastal research and coastal management.

[13] The project will initially seek to improve 1 Hz data by

[14] 1) analyzing the corrective terms and providing the best solutions, including those derived from proper local modelling;

[15] 2) developing a set of algorithms to automate quality control and gap-filling functions;

[16] 3) determining more thorough testing and validation strategies.

[17] These improved products will be delivered to users using Grid technology, allowing a deep assessment of the 1 Hz data performance and limitation over a wider range of coastal conditions (e.g., land topography, waves, winds, tides, etc.). The work outlined above will provide the input to a second phase of the project, where the feasibility and advantages of extending the processing chain to higher rate streams will be investigated. This is an extension based on the fact that currently operating altimeters such as Jason 1 and Envisat missions have been designed to provide a 20 Hz data stream which lends itself to be employed for

coastal-oriented processing. High rate data streams (10 Hz) were also available from Geosat, GFO and ERS satellites. However these were much noisier than Jason and Envisat so the real utility of the high rate data from these instruments will be assessed.

Research Programme

[18] This two-year program is specifically oriented to: a) improving satellite altimetry along the coasts of the Mediterranean, Caspian, Black, White and Barents seas and b) to allowing access to the improved data by a Grid-compliant architecture. As such, it has two complementary and interconnected components: one is the definition and development of an advanced altimeter data processing system, and the other is the design and implementation of a structure for efficient access to distributed archives of data.

[19] The altimeter processing stream will be built upon the Radar Altimeter Data System (RADS) [*Schrama et al.,* 2000] and will extend that system to address coastal user requirements and specific processing issues, by employing corrections optimized for the coastal environment and all available complementary local metocean information from various data sources (e.g., tide gauges and wave sensors; weather stations; high-resolution models; etc.). For example, regional corrective models for the atmospheric and tidal effects will be used, e.g., MOG2D, [*Carrère and Lyard,* 2003] for the Mediterranean Sea. Any improvement in the quality of the data will be benchmarked against independent in situ measurements. The ALBICOCCA site at Capraia Island (NW Mediterranean), for which there is a long continuity of altimetry monitoring, will be the pilot benchmark site; in addition to it, some coastal sites of opportunity will be selected on the basis of ground-based data availability from cooperative efforts like ESEAS, SELF, SONEL or national networks (e.g., Italian, Russian, Azerbaijan, etc.) in proximity of altimeter ground tracks. For instance, historical and current data on the Caspian Sea level from several coastal meteo stations in Azerbaijan [*Mamedov,* 1997, 2000; *Mamedov et al.,* 1999] will be used for comparison over that basin. Finally, the processing system will be applied to the whole length of the coast in the major basins.

[20] The system for efficient access to distributed archives of data will be based upon the Grid concept. Its structure will consist of regional data centres, each one with primary responsibility for maintaining its regional-archives by selecting the best corrections and ensuring quality control. Centres will operate a Grid-compliant set of web-services allowing access to the full functionality of data extraction, and a central web server will provide a simple interface to the web services to give interactive access to users. Particular attention will be devoted to the visualization and dissemination of the product to users such as modellers and forecasters, and to this effect a grid compliant application will be built and demonstrated over a number of case studies. The project will also made available a dissemination package in the form of a DVD, in a fashion similar to what the European Space Agency has done with the "River&Lake Product from Altimetry" (ENVISAT-ERS, 2004, http://earth.esa.int/riverandlake/docs/Product-Hand-book-1-2.pdf).

Approach and Methodology

[21] The project will adopt an approach starting from the indications of the users, which entails the following points:

[22] 1) identifying and understanding the user needs in terms of problems (e.g., coastal protection from increasing sea level and/or changing wave climate), procedures (e.g., calibrate models), products (e.g., sea level; wave height) and specifications (e.g., accuracy level), on the basis of what is currently available (e.g., tide gauges; wave sensors), and highlighting how altimetry can help (e.g., better coverage);

[23] 2) evaluating what can be done with the "official" products and what are the major issues, e.g., deficiencies in existing data streams and their handling, quality controls, error components;

[24] 3) determining what data processing steps need to be improved for adding value, e.g., use of available retracked products, use of 10/20 Hz data, correction updates, new processing functions;

[25] 4) addressing the required validation exercises;

[26] 5) going from the sensor measurement to a product, e.g., quality-controlled coastal sea level anomalies and significant wave height;

[27] 6) raising the awareness of altimetry data amongst the user community via a dissemination package;

[28] 7) distributing the products efficiently via a Grid-compliant portal which allows fully functional and custom extraction of optimized data to the users.

[29] In methodological terms, the process will include:

[30] 1) acquiring all available satellite data (1 Hz streams to start with, possibly higher rate streams later) over the regions of interest;

[31] 2) compiling local data sets, including tide gauges, metocean observations and model output;

[32] 3) characterizing the coastal region by taking into account the non-uniform conditions, e.g., bathymetry, land morphology, tides, wind;

[33] 4) analyzing initial data capabilities, e.g., anomalies, critical factors;

[34] 5) building processing chain, e.g., adjust corrections, add new or improved local corrective terms;

[35] 6) defining data match-up exercises, e.g., discrepancies, confidence levels;

[36] 7) building a server for the improved products.

[37] This methodology has two main benefits: a) it will make coastal altimetry data of higher quality than the currently available products, and b) it will make the data immediately available to modellers and data integrators.

Preliminary Results

[38] With respect to planned work the following results were achieved during the first year of the project:

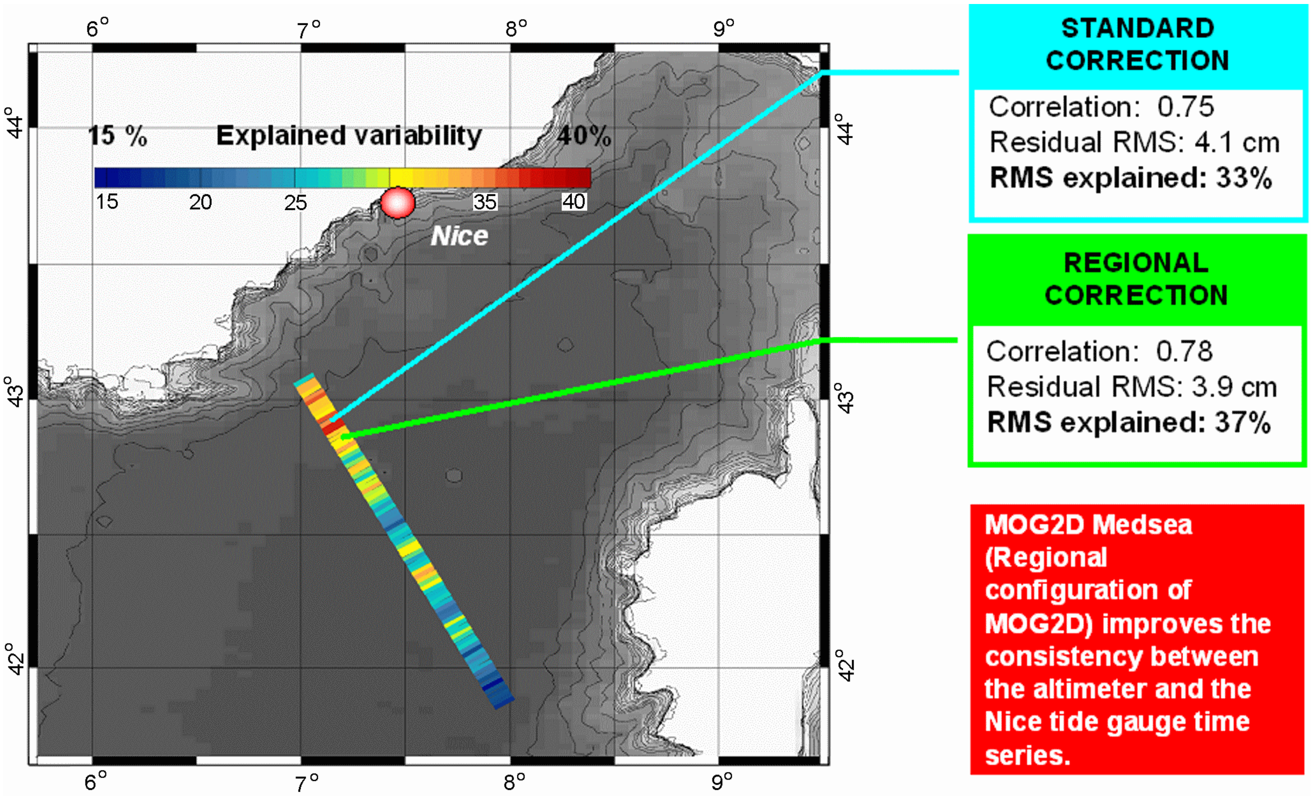

Figure 1. Impact of regional tidal corrections (Mediterranean Sea).

Mediterranean Sea

[39] The work in the Mediterranean Sea contributed to the development and improvement of the coastal altimeter data processor, working by screening multiple along-track altimeter data together, rather than individual ground points. This methodology permits both better determination of abnormalities caused by the altimeter and the radiometer (impacting on wet tropospheric and ionospheric path delays for instance), and retrieval of invalid corrective terms (by high order polynomial interpolation). With respect to Ssalto/DUACS products, this innovative methodology allows use of more altimeter data in the coastal ocean and ensures improved quality of the derived products. The coastal altimeter processor also improves local corrections for ocean tides & short period atmospheric forcing (Mog2d-Medsea) and computes a new local Mean Sea Surface (MSS) (Figure 1).

[40] Several results have been obtained using the new data screening, de-flagging and re-interpolation, demonstrating how they lead to a reconstructed sea level profile, which is then de-aliased using a regional model. A higher resolution MSS (including across-track effects) has also been computed from an inverse method – least-square fitting on the altimetry. This MSS is along track with a 5-point grid across-track. Differences with respect to the CLS01 MSS are significant in proximity to the coast. The wet tropospheric correction – and the land flag based on radiometer values – are still the main cause of both data drop-out and reduced data quality. Over the Mediterranean Sea the work is well advanced: we use multi-mission altimetry, data editing and state of the art corrections (Figure 2).

Black Sea

[41] Monitoring the mesoscale water dynamics in the Black Sea is a very important application of altimetry. It is well known that the circulation displays a chain of anticyclonic eddies, transported cyclonically by the Rim current around the basin. Smaller eddy features, with intense anticyclonic eddies and upwelling are present in the northeast, with some anticyclonic eddies along the southern coast and high chlorophyll concentrations at the mouth of the Danube River. Some comparisons have been made between SST and/or chlorophyll maps of the Black Sea against the TOPEX/ERS 2 composites that SIO get from CCAR mapped to 3 day. From the comparison it is clear that the small anticyclonic, long-lived eddies (60–80 km) along the Anatolian coast in the southern part are not resolved in the CCAR data (Figure 3). Other examples highlight how the standard altimetric products miss some important features at the mesoscale, despite capturing the overall circulation at basin scale and the largest eddies in the centre of the basin. This underline the need for an improved product in this basin. The performance of altimeter-derived measurements (and model measurements contained in the RADS

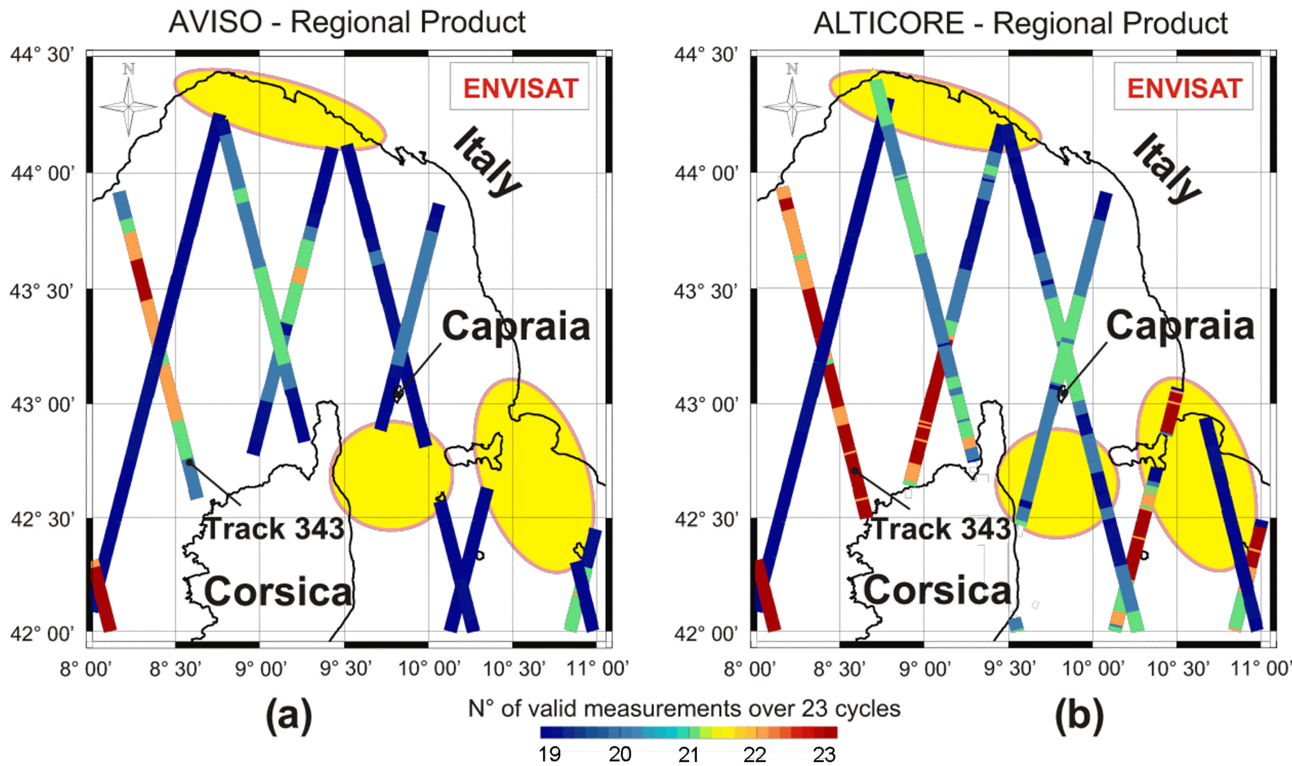

Figure 2. Comparison between the number of valid ENVISAT data (over 23 cycles from 22/05/2003 to 14/09/2005) obtained in the test area (Ligurian Sea) when using official regional AVISO (a) and our improved coastal altimeter data set (b). Only cases with more than 75% of cycles are plotted.

regional archives) were also investigated in relation to the sea level and meteo station data (wind) data. The ground tracks closest in space to the in situ stations were extracted and the data closest in time to the altimeter passes were selected. With reference to wind amplitudes, correlations in time are not very good – 0.3–0.4 – as shown by scatter-plots. With reference to sea level, correlations with respect to Jason-1 and Envisat are not very high. High mesoscale activity might be the reason for the observed discrepancy.

Caspian Sea

[42] In Central Asia, the application of satellite altimetry has a particularly important role for water availability monitoring. For the Caspian Sea satellite altimetry can help estimate the water budget. The Caspian shows a strong annual signal and interannual trends, including an increase from 1992–1995 followed by a fall to 2001–2002 (Figure 4).

[43] A technique for estimating the water budget has been illustrated, using an example of runoff from the Caspian Sea into the Kara Bogaz Gol (KBG) Bay. The comparison of altimeter-derived Caspian annual mean sea level with tide gauge data from different stations generally shows good agreement, but with some discrepancies (up to 7 cm in 1995). There are apparent inconsistencies between different tide gauges – some show increases when others are dropping – and although part of this difference might be due to geographical variability, the differences seen at long temporal scales are likely to be due to problems with the gauges. It is therefore difficult to infer water balance with such problematic in situ data. 10 years of T/P altimeter data were studied to derive the maps of amplitude of the annual signal. The altimetry processing is challenging with the problems of ice and the dry tropospheric correction when working on lakes. The value of the dry tropospheric correction is altitude dependant, but T/P GDRs icorrectly compute the correction at sea level, while for other satellites the correction is calculated strictly following the topography – i.e. to the lake bed. There are also land movements, which should be (and are not) accounted for. From an oceanographic point of view, in the Caspian Sea the situation is more complex than for the Black Sea as there are also some cyclonic eddies. Tests with a TOPEX radiometer-derived wind speed show it to be unreliable, normally much higher than model or altimeter-derived wind speed. A Mog2d high frequency model for the Caspian Sea at 7 km resolution offshore, reducing to 1.5 km at the coast, is under development to compute tides to be used for the tidal correction in the X-TRACK processor. The derived standard deviation of SSHAs along some Jason tracks (using 1 Hz data) shows some weak oceanographic signals close to the coast (plus the artefacts due to islands). There is a need for in situ data for validation and to confirm the regional wind response in the model. Concerning the analysis of the

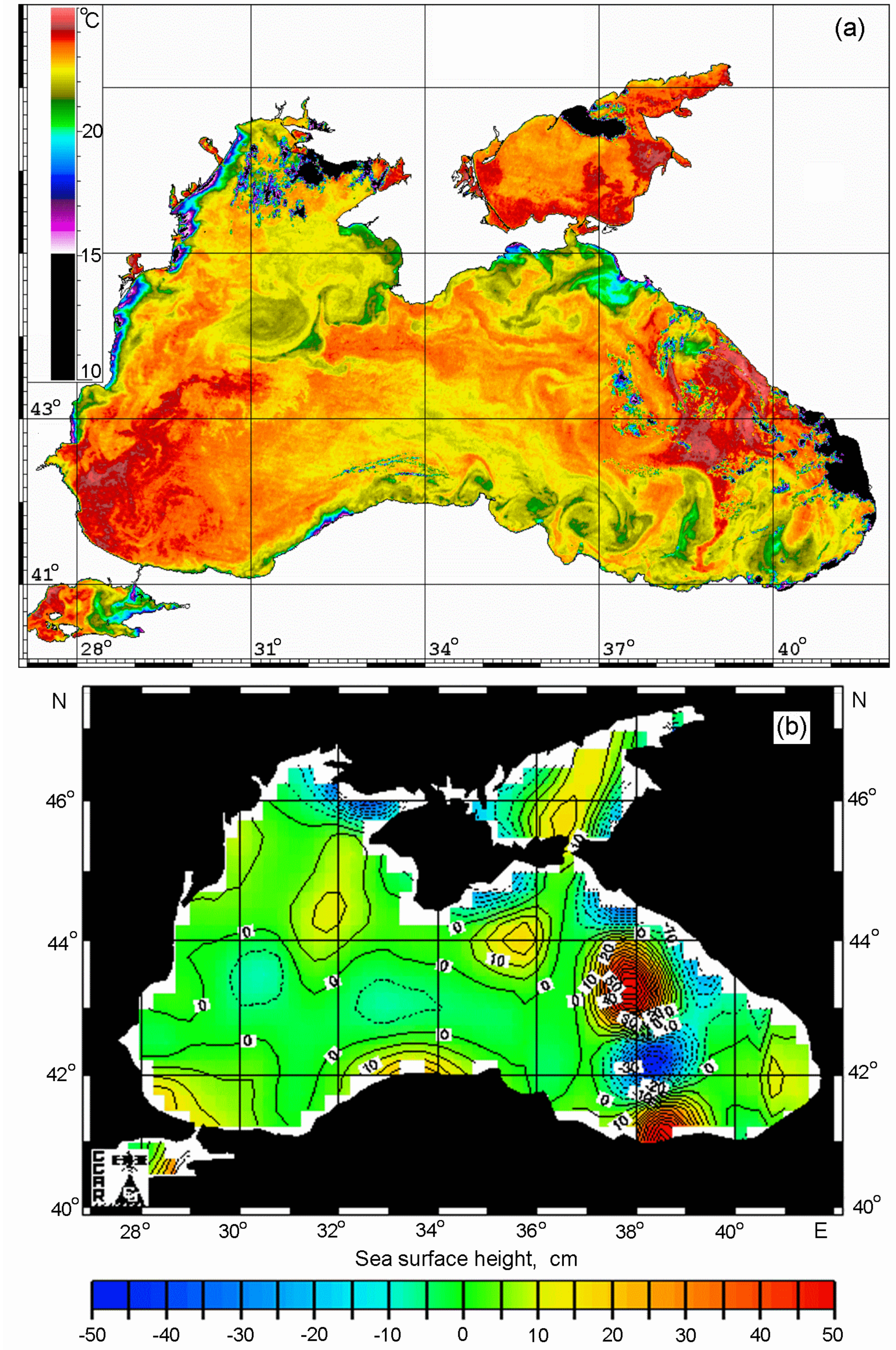

Figure 3. IR image of the Black Sea for 29 June 1998 (top panel) and corresponding SLA map for 28 June 1998 (bottom panel).

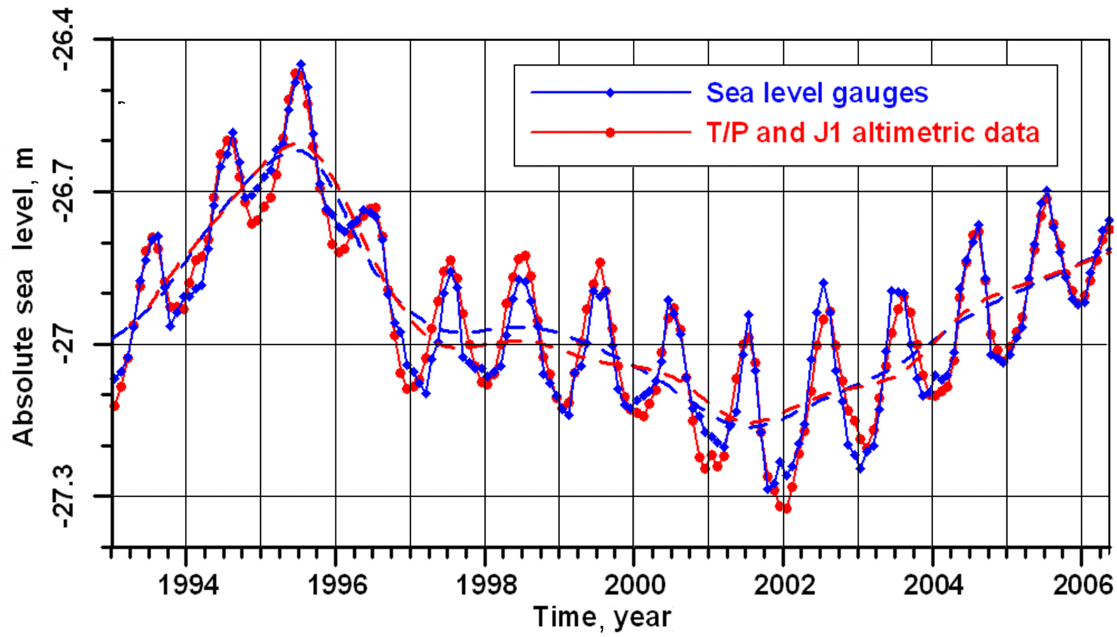

Figure 4. The Caspian Sea level variability in January 1993–January 2006 revealed from the T/P and J1 data (blue) and sea level gauges (red).

synoptic dynamics induced by atmospheric forcing and Volga River discharge, a Mean Sea Surface Model GCRAS06 was created, which is not influenced by interannual changes of the Caspian Sea level (Figures 5 and 6).

White and Barents Seas

[44] The physical characteristics of the Barents Sea and exchange with the nearest seas have been studied. The average depth of the basin is >200 m and the deepest point is >600 m. The White Sea is located at the southernmost part of the Barents Sea. Many factors influence the hydrodynamic regime of these seas, including the tidal regime (up to 8 m amplitude in some places). In RADS these tides can be corrected with FES99 or GOT00 (the latter is the choice recommended by RADS authors). But both models have 0.5° grid – too coarse to properly resolve the White Sea. GC suggests that in this area we should use the HRCRF (Hydrometeorological Research Centre of the Russian Federation) tidal model. This differs from GOT by up to 4 m in some places, for instance at the entrance of the White Sea (Figure 7). Another issue in this region is the Earth's crust uplift, which can be up to 4 mm yr^{-1}. Storm surges are also important and may reach 2 m in the strongest events. The coverage of this area by different satellites was discussed – T/P and Jason only marginally touch it. GFO is good for the White Sea, while ERS and Envisat cover all the White and Barents seas. The ice-free period is Apr/May to Oct/Nov for the White Sea. There was consensus that this is an appropriate area to show the possible improvements due to the adoption of regional tidal models as opposed to global models. Correlations of sea level from altimetry and tide gauge data can be fairly high (>0.9) for the Barents Sea using ERS data. For Geosat in the Barents Sea the correlations are noticeably lower, probably due to orbit errors and more inaccurate corrections. Correlations are extremely high when ERS-2 and Envisat are used in combination with two Norwegian tide gauges for which there are long, high-quality time series (Figure 8). These high correlations might be explained by tide effect, which are very significant in the Barents Sea. One might be recommended to remove the tides both from satellite data and from tide gauges data and then make a comparison. Still for the White Sea, but this time with ERS-2 data, which cover the whole basin, the correlations are significant. The White Sea is also affected by tidal rips, a modification of roughness when tidal currents converge in a narrow channel, which is very difficult to model. Finally, also in the White Sea there is a lot of scatter between in situ and altimeter/model data. To improve the correlation, additional tuned processing should be attempted (filtering, averaging).

Conclusion

[45] The expected outcomes of the ALTICORE project will be:

[46] (1) a set of quality protocols for coastal altimetry;

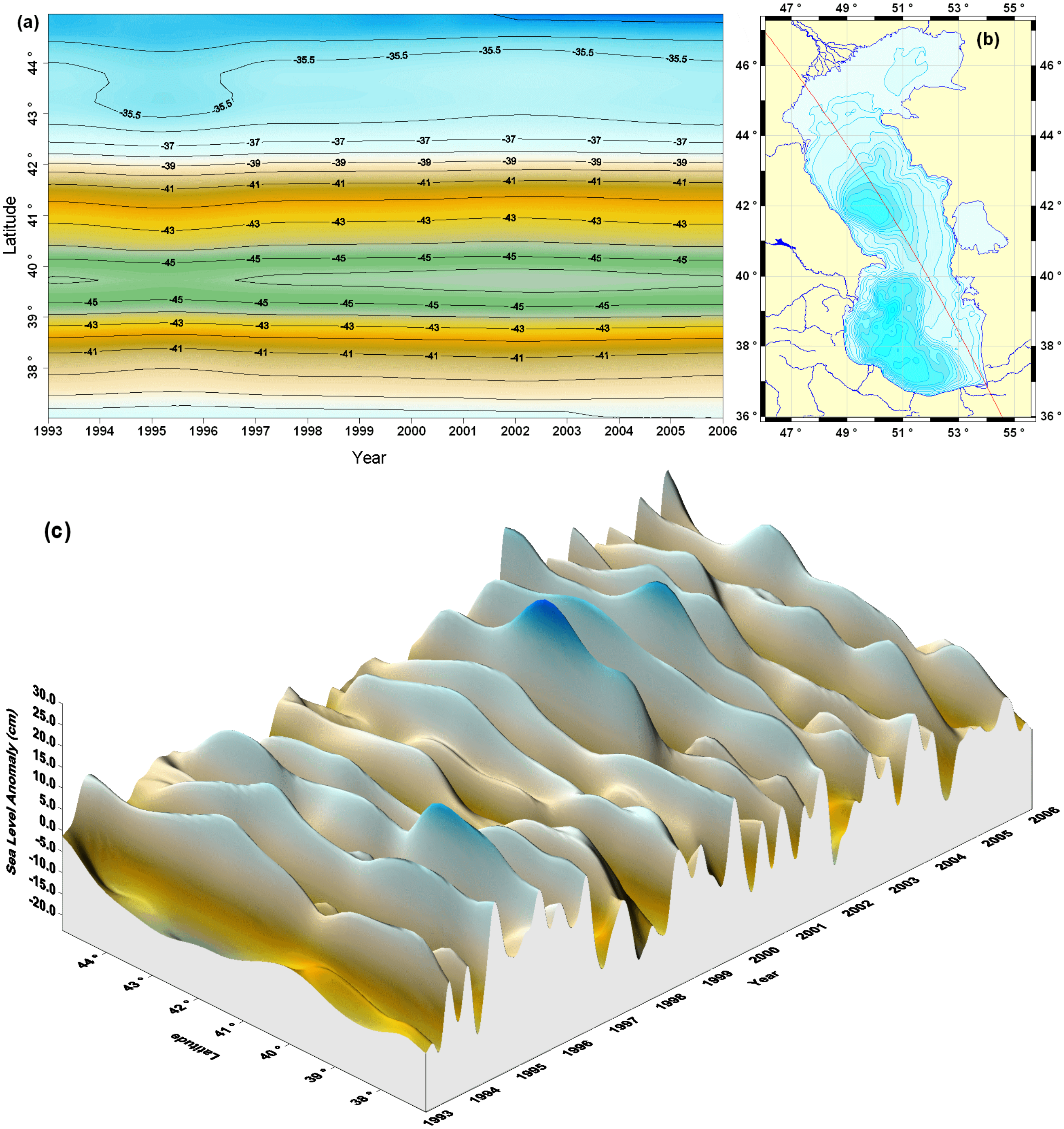

Figure 5. Time variability of the Caspian Sea SSH (m) without seasonal and synoptic variability (a), which was including in GCRAS06 MSS model along the descending 092 track (b). Time variability of the Caspian Sea SLA (cm) was calculated relative to on GCRAS06 MSS model along the same track (c).

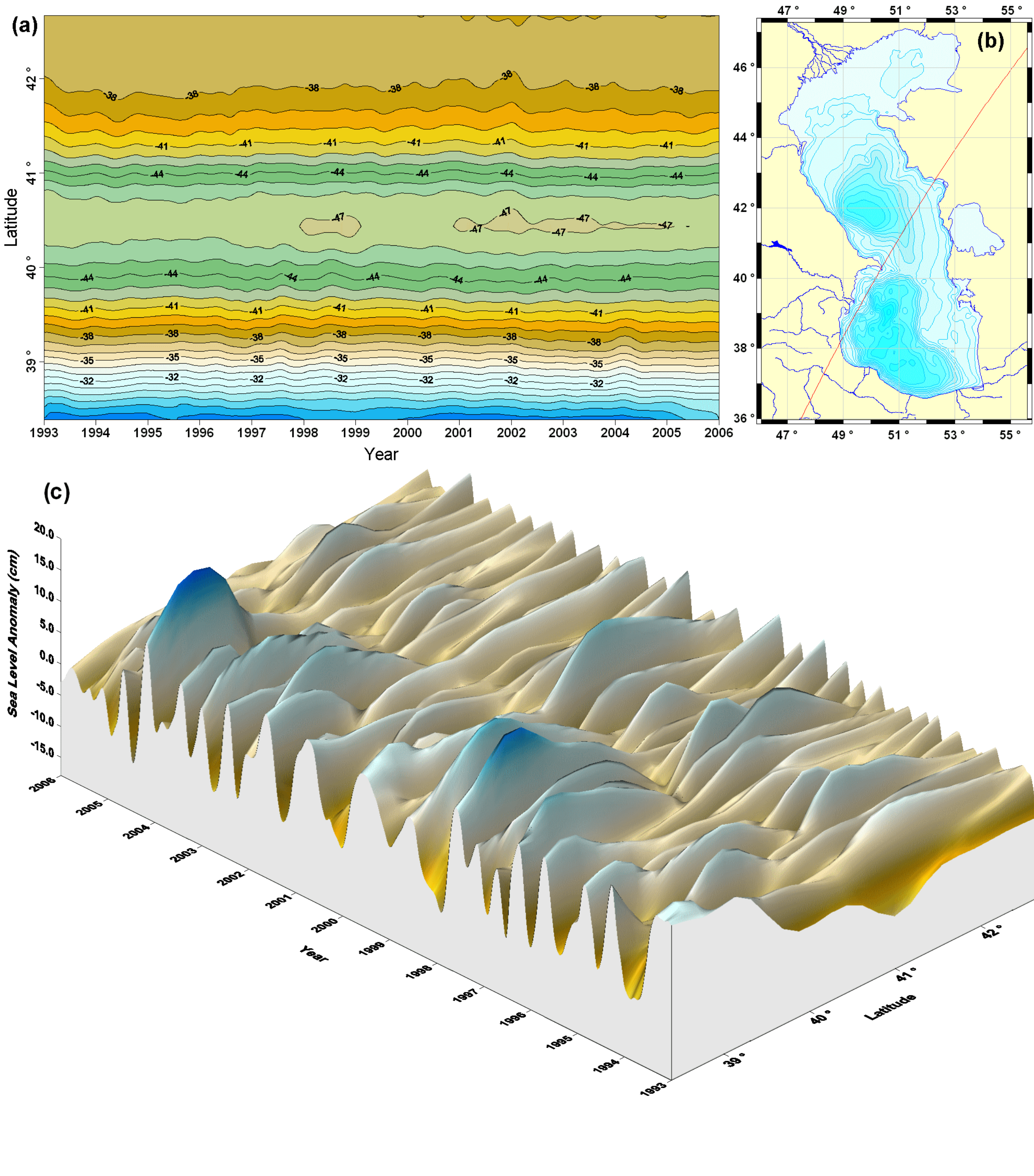

Figure 6. Time variability of the Caspian Sea SSH (m) without seasonal and synoptic variability (a), which was including in GCRAS06 MSS model along the ascending 209 track (b). Time variability of the Caspian Sea SLA (cm) was calculated relative to on GCRAS06 MSS model along the same track (c).

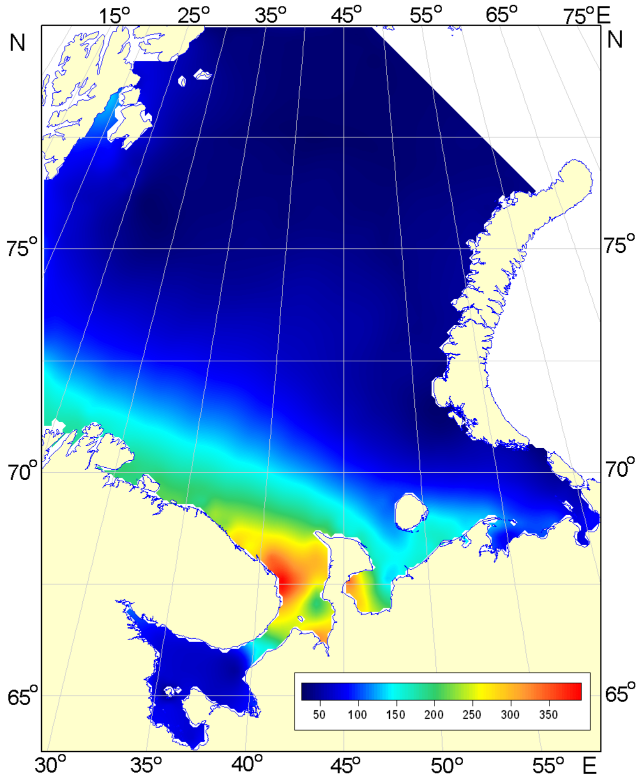

Figure 7. The comparison of results of calculation on the global model (GOT00) and on the Regional tide model HRCRF for Barents and White Seas. Maximal deviation of tide height (cm).

[47] (2) a set of improved altimetric corrections, algorithms and quality control procedures, optimized for coastal targets;
[48] (3) a system for the production of the improved, protocol-compliant altimetric products along the European coasts; the system will be configured as a Grid application and will include a portal for access to the improved data;
[49] (4) an outreach and dissemination package, in the form of a brochure plus a DVD with demonstrative data, targeted to users such as modellers, data integrators and forecasters.

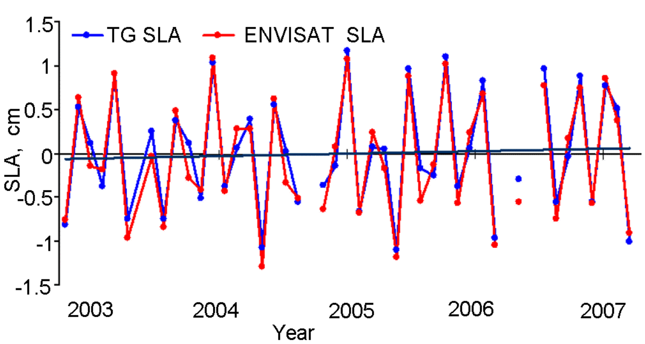

Figure 8. Sea level anomalies from the tide gauge (Hohhinsvarg) and ENVISAT (2002–2007).

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Sergey Lebedev, Alexander Sirota, Dmitry Medvedev, Svetlana Khlebnikova, Geophysical Center, Russian Academy of Sciences, 3 Molodezhnaya Str., 119296, Moscow, Russia

Stefano Vignudelli, Consiglio Nazionale delle Ricerche, Istituto di Biofisica, Area Ricerca CNR San Cataldo, 56127 Pisa, Italy, e-mail:vignudelli@pi.ibf.cnr.it

Helen M. Snaith, Paolo Cipollini, Fabio Venuti, National Oceanography Centre, European Way, SO14 3ZH, Southampton, UK

Florent Lyard, Jérôme Bouffard, Jean Francois Cretaux, Florence Birol, Laboratoire d'Etudes Géophysique et Ocèanographie Spatiale, 18 Av. E. Belin, 31401 Toulouse Cedex 9, France

Laurent Roblou, Noveltis, Parc Technologique du Canal 2, Avenue de l'Europe 31520, Ramonville-Saint-Agne, France

Andrey Kostianoy, Anna Ginzburg, Nickolay Sheremet, Elena Kuzmina, P. P. Shirshov Institute of Oceanology, 36 Nakhimovsky Pr., 117997, Moscow, Russia

Ramiz Mamedov, Khasiyat Ismatova, Amir Alyev, B. N. Mustafayev, Institute of Geography, Center for Caspian Sea Problems, H. Javid Str. 31, AZ1143 Baku, Azerbaijan