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Oceanography

Fig.1

Space techniques make a decisive contribution to ocean process understanding, ocean analysis and ocean forecast. The ocean is a remote area where permanent in situ monitoring is complex and expensive. Satellites are a unique opportunity to provide measurements with global coverage, appropriate time and space sampling, consistency, complementary to in situ measurements which provide in depth information. Active or passive sensors, optical or radio-frequency can be used to monitor multiple parameters describing the global ocean status in terms of dynamics and biogeochemical state. The ocean is a turbulent fluid and its variability covers multiple time and space scales. The former range seconds (waves) to hundreds of years (thermohaline circulation, climatic variations), whereas the latter range from centimeters to thousands of kilometers.

The results achieved by several space missions to which France has greatly contributed are presented below. In the last two years, major milestones for the CNES ocean programs have included the successful launch of JASON-3 and SENTINEL-3A, the completion of the SWOT Preliminary Design Review, the Critical Design Review of CRYOSAT and the beginning of the Copernicus Marine Environment Monitoring Service.

Nadir altimetry: monitoring sea level and ocean dynamics

Satellite altimetry has a unique ability to provide integrated three-dimensional information on the physical state of the ocean. Changes in ocean temperature, salinity or currents at sea surface or at depth induce changes in sea surface topography. The currently available technology relies on a nadir-looking radar combined with precise orbit determination to provide measurements of sea-surface elevation. An adequate large mesoscale sampling requires four satellites in orbit simultaneously, including one non-sun-synchronous orbit to sample the diurnal signal (JASON series).

Two recent successful launches represent major milestones for the future of the Ocean Surface Topography constellation:

- Launch of JASON-3 (U.S.-Europe cooperation) on January 17, 2016. Commissioning is progressing very well. The Flight Acceptance Review was successfully conducted in April 2016.
- Launch of the SENTINEL-3A mission (European mission in the framework of the Copernicus program)

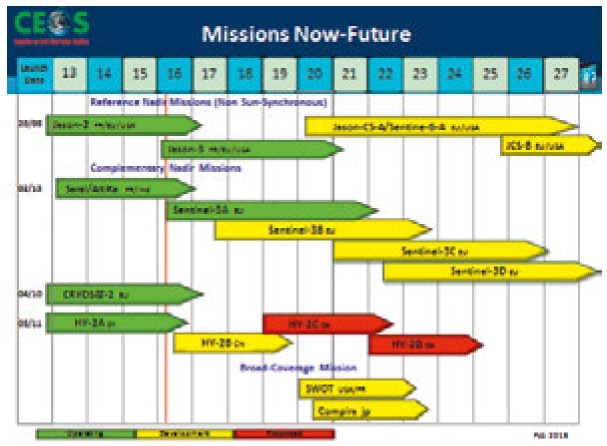

Fig.2

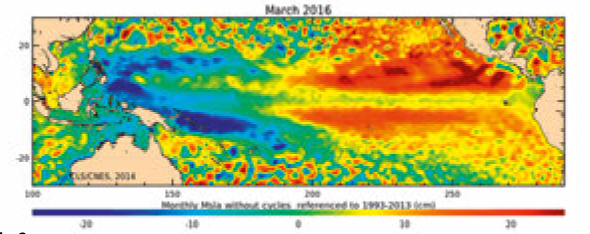

Fig.3

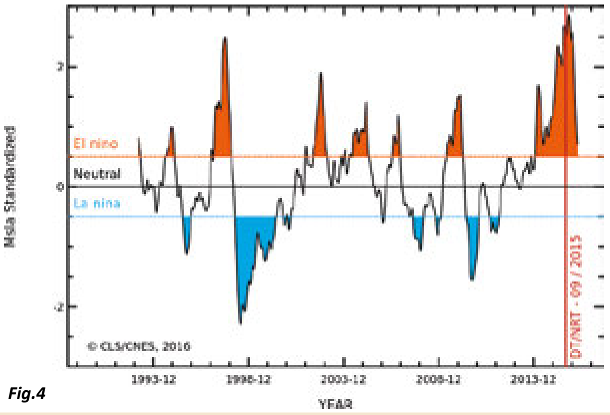

Fig.4

Fig. 1: Wave crashing in Cap Kiwanda (US) © *Thinkstock*

Fig. 2: Ocean Surface Topography Virtual Constellation status.

Fig. 3: El Niño monitoring using altimetry measurements.

Fig. 4: El Niño index evolution.

on February 16, 2016. SENTINEL-3 embarks an altimetry payload combining a radar altimeter, precise orbit determination instruments (DORIS, GNSS, a Laser Retro Reflector) and a radiometer to correct measurement from the radar signal affected by water. Commissioning of this payload is also progressing very well. The CNES contribution to this mission includes the DORIS payload, support to ESA/EUMETSAT project team for system performance, data processing and product definition, in-orbit validation.

These two new satellites will join, as soon as those missions will be operational, the current constellation composed of:

- JASON-2, which will be moved into an interleaved orbit with JASON-3 in order to optimize the combined sampling;
- SARAL/ALTIKA (Indo-French cooperation), which has demonstrated the improved performance that can be achieved using Ka-Band (better resolution and sensitivity applications to ocean, hydrology and cryology). SARAL has ended its three-year nominal lifetime mission at the end of February 2016 and is about to begin a two-year extended mission,
- HY-2 (Chinese-French cooperation),
- CRYOSAT (ESA mission) dedicated to ice topography measurement. Its additional goal is to provide highly valuable ocean surface topography measurement. CNES has, in particular, provided support for the development of optimized ocean products.

In this new configuration of the altimetry constellation, the requirements expressed in the CEOS OST-VC (Ocean Surface Topography Virtual Constellation) requirement document [1] will be met.

This set of missions are the opportunity to conduct significant science activities such as to monitor the mean sea level drift under climate change or to support operational oceanography, providing the necessary inputs for analysis and forecast of the ocean state to centers such as the Copernicus Marine Environment Monitoring Service.

The recent COP21 conference has highlighted the strong impact of the mean sea level index for the monitoring of the climate change process under way. This index, computed using satellite altimetry measurements, represents changes – in the thermal content of the ocean as well as in the ocean water mass – due to continental ice melting and mass exchange between continental waters and oceans.

The strong El Niño event which occurred in 2015 (see Fig. 3 and 4) also illustrated the importance of satellite altimetry to monitor and forecast such climatic events which have a strong impact on populations.

Wide-swath altimetry: SWOT, a new frontier for oceanography

Nadir altimetry technique allows successful monitoring of the ocean dynamics for time and space scales larger than 10 days and 100 km. However, ocean dynamics involve important processes which have smaller time and space scale characteristics. Their features must be characterized to gain a better understanding of the ocean and to support operational activities. This is the goal of the SWOT mission (in addition to inland water monitoring).

This mission will be the first flight of the KARIN high-resolution wide swath altimeter (about 120 km). The mission is conducted in cooperation between NASA and CNES. CNES takes responsibility for the platform and contributes to the payload through the development and delivery of the KARIN Radio Frequency Unit, the nadir altimeter, and the DORIS instrument.

The monitoring of ocean and atmosphere interaction, ocean physic and ocean biology interactions, internal waves and coastal dynamics requires a high-resolution observing system. These are some of the ocean scientific objectives of the SWOT wide-swath altimetry mission.

The preliminary design phase of the mission has been successfully achieved and the formal decision on the C/D phases should be made by mid-2016. The mission is scheduled to be launched in 2021.

In parallel, a common NASA-CNES Announcement of Opportunity has been released in 2016 to select the international science team that will contribute to the mission definition and prepare the use of the mission products. 26 teams from France and six other countries have been selected for ocean applications. They cover open ocean, coastal and ice objectives. Another set of teams has been selected for inland water applications.

This highly innovative mission faces multiple challenges: on the instrument, on the platform, on the ground system, and on science algorithm development to extract the pertinent information from the measured signal. This mission will open a new era for oceanography, as TOPEX/POSEIDON did about 25 years ago.

Sea state: ocean-atmosphere interface monitoring

The CFOSAT project (Chinese-French Oceanography Satellite) aims to measure the ocean surface wind and waves. It will embark on the same platform (provided by China) as the SWIM instrument dedicated to wave measurement (provided by CNES) and the SCAT instrument dedicated to wind measurements (under China's responsibility).

SWIM is a wave spectrometer radar. It uses a low-incidence radar covering incidence angles from 0° to 10° and having a rotative azimutal capacity. The innovative aspect of the sensor is its capacity to provide directional wave spectra, including short wavelengths whereas other instruments such as the SARs provide wave information for long wavelengths.

The SCAT scatterometer will use a rotating antenna for surface wind measurements.

The mission's primary objective concerns the study of sea surface processes: wind, waves and their coupling, the impact of waves on ocean currents and on atmosphere. As such, the mission appears highly complementary to SWOT. It also has an operational objective which is to improve sea-state forecasts.

CFOSAT is in the final stage of critical design and the launch is scheduled for 2018.

A special session at IGARSS 2015 was dedicated to the CFOSAT mission [2].

An Announcement of Opportunity to set up an international science team associated to the CFOSAT mission is scheduled to be issued in 2016.

Ocean salinity

The SMOS satellite (ESA-French-Spanish cooperation) has been in orbit since November 2009. It has provided highly valuable measurements of soil moisture when overflying the ground, and of ocean salinity when overflying sea surface.

The major contribution of CNES to this mission is the platform and a mission center, the CATDS, in charge of processing and distributing level 3 & 4 soil moisture and ocean salinity products.

The major achievement of the past two years concerning the ocean salinity measurement has been the significant improvement of the quality of ocean salinity products through the development of new measurement bias correction algorithms. SMOS measurements over sea surface are impacted firstly by the signal emitted by ground surfaces when they are present in the antenna field of view (about 1000 km) and secondly by the variations of sun angular direction on the satellite on-board sensor. This affects the measurements, which are rather complex to take into account, although recent developments have allowed the removal of these perturbing signals. Thanks to these improvements, the demonstrated capacity of SMOS to detect interannual variability changes in sea surface salinity is now at the level of 0.2 psu.

Specific sessions on ocean surface salinity measurements – and more specifically on SMOS – have been organized in various symposiums (EGU, IGARSS, etc.) and those measurements are now key elements, complementary to in situ measurements providing higher space resolution information (in particular for the 100 km, monthly space and time scale).

Ocean color

Ocean color monitoring is a unique tool for water quality and ocean biology monitoring. A major step was recently achieved with the successful launch (in February 2016) of SENTINEL-3A (Europe, EU, ESA) which carries a wide-swath (1 270 km) advanced ocean-color instrument (OLCI) providing global coverage and short revisit time (two days with the SENTINEL-3 A & B configuration). The OLCI sensor covers 21 spectral bands in the visible and near infrared wavelengths (from 400 to 1 020 nm). The CNES contribution to this mission is mainly through in-flight Cal/Val activities.

As a complementary component to the low earth orbit ocean color missions such as SENTINEL-3, CNES has conducted a phase 0/A study on a geostationary orbit mission concept that would embark an adapted ocean color payload as a hosted payload on board a telecommunication satellite. This mission named GEOCAPI would provide a high temporal sampling capacity, one hour for the full visibility disk from geostationary orbit coverage. In areas with little clouds this will allow to sample the diurnal cycles and to monitor algae blooms; in areas with more intense cloud coverage, this should guarantee a high revisit time, taking advantage of cloud free times during the day.

Taking advantage of similar initiatives in Asia (*i.e.*, GOCI II by South Korea) and in the US (*i.e.*, GEOCAPE by NASA), it should be possible, when those missions will be decided and implemented, to provide an almost full global coverage with three different satellites of high temporal sampling information on the ocean color.

Copernicus marine environment monitoring service

The European Union has set up the Copernicus Marine Environment Monitoring Service (CMEMS). Since May 2015, the CMEMS has worked on an operational mode, after the MyOcean demonstration phase enabled to open the service on a pre-operational mode during six years.
The Copernicus Marine Service has been designed to respond to issues emerging in the environmental, business and scientific sectors. Using information from both satellites and in situ observations, it provides daily state-of-the-art analyses and forecasts, which offer an unprecedented capability to observe, understand and anticipate marine environment events.
The CMEMS provides regular and systematic core reference three dimensional information on the physical and biological state of the global ocean and European regional seas. The observations and forecasts produced by the service support all marine applications.
CNES is a partner of the consortium and is in charge of ensuring that the CMEMS provides high level altimetry products which are assimilated into the ocean models. This consortium is led by Mercator Ocean (France) and gathers partners from all over Europe.

Fig. 5: Whith 90,000 people living in an area of 1,9 sq.km, Malé, the capital of the Maldives, is one of the world's most densely populated cities. © *Thinkstock*

Pole ocean – data and services for oceanography

Ocean data access has been largely facilitated by the setting up of various international programs such as the EU Copernicus program (CMEMS) or the ARGO program (a global array of more than 3 000 free-drifting profiling floats that measures the temperature and salinity of the upper 2 000 m of the ocean).

CNES is a partner of the CMEMS and contributes to the ARGO program through the ARGOS data collection system which allows quasi real time data recovery.

Although the CMEMS, ARGO and other programs are key elements for oceanographers, they do not cover the necessary complete set of data, especially coastal in situ measurements which are collected through various individual initiatives. It has been decided that a new service in France would be created: the "Pôle Océan" will set up a coordinated information system to provide the necessary data for oceanography, connecting all existing ocean databases and providing a unified access to users.

REFERENCES

[1] Wilson, S., *et al.* (2012), The Ocean Surface Topography Constellation: the Next 15 Years in Satellite Altimetry, CEOS.

[2] Tison, C., *et al.* (2015), Processing of the CFOSAT-SWIM data : IGARSS 2015, Milano, Italy, Jul 2015, 4p.

[3] Kolodziejczyk, N., *et al.* (2015), SMOS salinity in the subtropical North Atlantic salinity maximum: two-dimensional thermohaline variability, *Journal of geophysical research: Oceans*, **120**(2), 972-987.doi:10.1002/2014JC010103.

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Oceanography

Sea-level rise monitoring

Sea level varies globally and regionally, on a broad range of temporal and spatial scales, in response to climate change and variability, as well as to solid Earth's deformations caused by land ice melt, among others. Satellite measurements have proved to be key elements to monitor and understand sea-level changes. Satellite altimetry provides a global and homogeneous data set which has become a reference for mean sea-level change monitoring at global and regional scales. Combining these measurements with others (e.g. gravity from space, in situ hydrographic data) allows to better understand the causes of sea-level variations and to close the sea-level budget. This article provides an overview of recent results on this topic.

Global warming as a result of anthropogenic greenhouse gas emissions has already shown several visible consequences, such as the increase of the Earth's mean air temperature and ocean heat content, and the melting of glaciers. Ocean warming and land ice melting are causing sea level to rise, with potentially negative impacts in many low-lying areas of the world. The precise measurement of sea-level changes as well as its different components, at global and regional scales, is a major issue for a many reasons. It provides information on how the climate system and its components respond to global warming. This allows validation of the climate models developed for projecting future changes.

The Global Climate Observing System (GCOS) has recently defined a set of 50 climate variables (called Essential Climate Variables – ECVs) that need to be precisely monitored in the long term in order to improve our understanding of the climate system, its functioning and its response to anthropogenic forcing, as well as to provide constraints for climate modeling [1]. Sea level is included in this list of ECVs.

After a 130-meter rise during the last deglaciation - which followed the last ice age, between - 20 000 years BP and - 4 000 years BP- sea level remained stable until the beginning of the industrial era. During the 20th century the global mean sea level started to rise with a mean rate of 1.7 ± 0.4 mm/yr. Since the beginning of the 1990s, this rise has reached 3.3 ± 0.5 mm/yr, as seen from satellite altimetry measurements and confirmed by tide gauge records [2].

Significant progress has recently been made to better characterize and reduce the error associated with sea-level measurements at global and regional scales. This has, in particular, been done as part of ESA's Climate Change Initiative program [3] in order to meet the GCOS's accuracy requirement (0.3 mm/yr for the global mean sea-level rate).

Figure 1 was extracted from the Aviso+ website (and is regularly updated) and provides the evolution of the global mean sea level, computed from altimetry satellites, between 1993 and 2016. As evidenced by this curve, the linear trend mentioned above is combined with a significant interannual variability. The latter is related to El Niño–Southern Oscillation through its impact on the global water cycle [4]. When correcting for this interannual variability, the global mean sea level's apparent slowdown in the last decade (due to a succession of La Niña episodes causing temporary sea-level drop) disappears, leading to a similar rate of sea-level rise (of 3.4) during the first and second decade of the altimetry era [2], but with a higher uncertainty (0.7 mm/yr) in the first than in second (0.4 mm/yr).

To demonstrate the causes of the global mean sea-level rise, one may combine altimetry with other measurements. Space gravity missions in particular (mostly the GRACE mission which provides information on mass redistributions at the surface of and within the Earth) measure the changes in ocean mass variations and glacier and ice-sheet mass balance, as well as land water storage variations [5]. Temperature and salinity profiles from in situ measurements (Argo program) monitor ocean heat content changes by providing information on the ocean thermal expansion. Over the 1993-2010 timespan, global mean sea rise can be attributed to ocean thermal expansion (30 to 40%), continental ice melting (about 50%) and exchanges between ocean and land water storage (10 to 15%) [6].

Recent publications have studied the global mean sea-level budget to investigate whether it is possible to constrain the deep ocean contribution (not measurable by Argo) to the global mean sea-level rise over the last decade. This question is particularly relevant, considering the current debate about the "hiatus" *i.e.*, the observed recent pause of the global mean air and sea surface temperature evolution while the planet is still in radiative

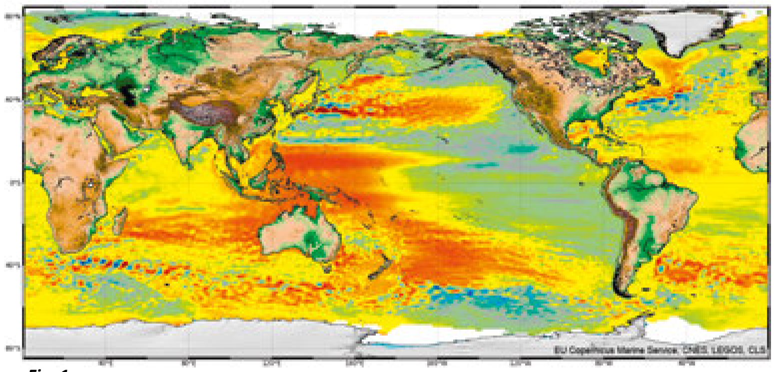

Fig. 1

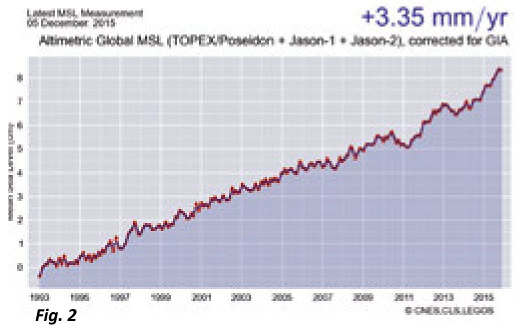

Fig. 2

Fig. 1: Mean sea-level change computed from satellite altimetry (TOPEX/POSEIDON, Jason1, Jason 2), ref Aviso website (http://www.aviso.altimetry.fr).

Fig. 2: Sea-level change map computed from satellite altimetry (TOPEX/POSEIDON, Jason1, Jason 2), ref Aviso website (http://www.aviso.altimetry.fr).

imbalance [7]. No significant rise in the temperature of the bottom layers (< 2 000 m) can be evidenced at present. The residuals between observed global mean sea-level rise and the sum of the ocean mass and steric (down to 1 500 m) component appears dominated by uncertainties on the parameters used for these estimations: gaps in the Argo data coverage and remaining Argo errors, GRACE and altimetry-based sea-level measurements. However, this analysis demonstrated significant warming of the 700–1 500 m ocean layer.

Satellite altimetry measurements highlight significant variability of sea-level change at regional scale. Regional variability is mostly due to non-uniform ocean thermal expansion [8]. Thermal expansion heterogeneity is largely caused by the natural interannual ocean circulation variability at regional scale in response to the atmospheric forcing. The natural variability is significant in numerous areas so that sea-level trend patterns may still be due to internal climate variability, the anthropogenic forcing signal being still low at regional scale. Many recent studies have analyzed spatial trend patterns in sea level in various basins. In the tropical Pacific, for example, [9, 10] the thermocline deepening due to increasing zonal wind stress during the past two decades has been demonstrated to govern most of the observed sea-level changes and trends in the tropical Pacific. This natural variability still masks the anthropogenic impact on the local sea level in satellite observations.

10% of the world population is living in coastal areas less than 10 m above sea level. The adverse effects of sea-level rise in coastal areas are considered a major threat of climate change. Twentieth century observations report shoreline erosion in many areas of the world coastlines which can be related to various causes including sea-level rise due to storm surges, wave and current regime change, ground subsidence (causing relative sea-level rise), coastal management, land use changes, deficit in sediment supply, etc. It is virtually certain that in the coming decades, the expected acceleration of sea-level rise in response to continued global warming will exacerbate the vulnerability of many low-lying, densely populated coastal areas of the world; in the near future, it will very likely become a major threat to a significant fraction of human beings. To prepare for such impacts, dynamic global sensitivity analysis of marine flooding to input parameters such as sea-level rise and local coastal processes has to be developed [11].

REFERENCES

[1] GCOS: Systematic Observation Requirements for Satellite-Based Data Products for Climate (2011 Update) – Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)", GCOS-154, WMO, December 2011.

[2] Cazenave, A., *et al.* (2014),The rate of sea-level rise, *Nature Climate Change*, **4**, 358–361.DOI 10.1038/NCLIMATE2159/

[3] Ablain, M., *et al.* (2015), Improved sea level record over satellite altimetry era (1993–2010) from the Climate Change Initiative project, *Ocean Sciences,* **11(1)**, 67–82.

[4] Cazenave, A., *et al.* (2012), ENSO influence on the global mean sea level over 1993-2010, Marine Geodesy, **35(S1)**, 82–97.

[5] Chambers, D. P. (2006), Evaluation of new GRACE time-variable gravity data over the ocean. Geophysical Research Letters, **33(17)**, L17603.

[6] Church, J. A., *et al.* (2013), Sea Level Change. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.*

[7] Dieng, H.B., *et al.* (2015), The Sea Level Budget Since 2003: Inference on the Deep Ocean Heat Content, Surveys in Geophysics, **36 (2)**, 209-229.DOI: 10.1007/s10712-015-9314-6

[8] Meyssignac, B., *et al.* (2016), Causes of the regional variability in observed sea level, sea surface temperature and ocean colour, *Survey in geophysics,* GEOP-D-16-00027.

[9] Palanisamy, H., *et al.* (2015), Spatial trend patterns in Pacific Ocean sea level during the altimetry era: The contribution of thermocline depth change and internal climate variability, Ocean Dynamics, **65 (3)**, 1–16.DOI:10.1007/s10236-014-0805-7.

[10] Palanisamy, H., *et al.* (2015), Is anthropogenic sea level fingerprint already detectable in the tropical pacific ocean? Environ. Res. Lett., **10**.DOI : doi:10.1088 1748-9326 10 8 084024

[11] Goneri Le Cozannet, G., *et al.* (2015), Evaluating uncertainties of future marine flooding occurrence as sea-level rises, *Environmental Modelling & Software*, **73**, 44-56.