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Report describing results to European services and projects contributing to Climate monitoring

1 Introduction

1.1 Purpose and scope

The purpose of this document is to describe the results obtained in LOTUS to European services, which might benefit from the results and their value for climate monitoring.

1.2 Essential climate variables

To ensure knowledge of the climate and its monitoring, the Global Climate Observing System (GCOS) program has developed the concept of "essential climate variables" (ECVs) (GCOS 2010). These 50 variables cover the various components of the climate and are listed in Table 1. In the table the variables that are estimated or can be derived from the LOTUS products has been underlined. For the Ocean part these are; Sea level, Sea state, and for the terrestrial part these are; River discharge, lake (levels), Soil moisture (and snow depth). When presenting the results obtained in LOTUS in section 3 we will use the ECSs as the starting point.

Table 1: Essential climate variables

The essential climate variables (for qualifying details, see GCOS 2010).		
Atmospheric	Surface:	Air temperature, wind speed and direction, water vapour, pressure, precipitation, surface radiation budget
	Upper air:	Temperature, wind speed and direction, water vapour, cloud properties, Earth radiation budget (including solar irradiance)
	Composition:	Carbon dioxide, methane, other long-lived greenhouse gases, ozone and aerosol supported by their precursors
Oceanic	Surface:	Sea surface temperature, sea surface salinity, sea level, sea state, sea ice, surface current, ocean colour, carbon dioxide partial pressure, ocean acidity, phytoplankton

	Subsurface:	Temperature, salinity, current, nutrients, carbon dioxide partial pressure, ocean acidity, oxygen, tracers
Terrestrial		River discharge, water use, groundwater, lakes, snow cover, glaciers and ice caps, ice sheets, permafrost, albedo, land cover (including vegetation type), fraction of absorbed photosynthetically active radiation, leaf area index, above-ground biomass, soil carbon, fire disturbance, soil moisture

1.3 Satellite radar altimetry

A short description of Satellite radar altimetry and its basic principle is presented below to accommodate the reader that is unfamiliar with this measurement technique.

The principle of satellite radar altimetry is fairly simple. A radar impulse with the speed of light is emitted from the satellite and reflected at the surface. Hence, from the two-way travel time we can determine the distance between the satellite and the surface, the range as:

$$R = \frac{c}{2}\Delta t$$

Where Δt is the two-way travel time and c is the speed of light.

If the position of the satellite is known with respect to a reference surface (an ellipsoid), we can determine the elevation of the surface with respect to the reference surface as:

$$H = h - R,$$

where h is the altitude of the satellite. To accurately derive the surface elevation H various (atmospheric, geophysical, and instrumental) corrections must be applied.

Radar satellite altimetry has now been used for several decades. One of the first satellites to provide useful results was the satellite Seasat (1978) (Aviso, 2016). The technique was originally intended to measure the sea level, but has since become applicable to other surfaces such as sea ice, ice sheets and continental water.

The current collection of altimetry data comprises a continuous image of the Earth in both space and time, which makes it possible to study various changes on the surface of the Earth such as sea level change, and changes in the elevation of the ice sheets. Satellites altimetry and its derived products are therefore unique tools in relation to climatic studies.

The launch of the ESA mission CryoSat-2 in 2010 has marked a new era in radar altimetry, since it is the first satellite that carries a SAR altimeter on-board. The SAR altimeter "SIRAL" has a footprint of approximately

300 m in the along-track direction, while it is comparable to conventional altimeter in the across-track direction. The smaller footprint makes it possible to measure the water level more accurately closer to the coast and for smaller continental water bodies. The SAR altimeter will especially allow for more accurate water level estimates over coastal and inland water areas – especially when the track lies perpendicular to the coastline. Unlike CryoSat-2, which operates in LRM, SAR, and SARIN mode depending on a geographical mode mask, Sentinel-3 will operate in SAR mode globally at all times.

1.4 LOTUS

One of the prime objectives in the LOTUS (Land and Ocean Take Up from Sentinel-3) project has been to develop methodologies to process and analyse SAR mode satellite altimetry data for both ocean and land. The original intention in the project was to apply sentinel-3 data, but due to the delay of Sentinel-3, only CryoSat-2 data has been applied. It is important to notice that CryoSat-2 and Sentinel-3 have very different track patterns. CryoSat-2 has a repeat orbit of 369 days, which implies that the spatial resolution is very high; with an Equatorial track spacing of just 8 km. This configuration makes it more challenging to construct time series of the water level, since the surface topography must be accounted for. Sentinel-3 will have a repeat orbit of 27 days; this on the other hand implies that the spatial resolution is significantly lower compared to CryoSat-2.

1.4.1 LOTUS data and test areas

The available LOTUS products per sub theme and test area are summarized in Table 2 below. The data sets are available from the following ftp-sit ftp://ftp.spacecenter.dk/pub/EU-LOTUS/ or https://nas-ext.cls.fr:443/fbsharing/PRPt1Kuc. All the products except the soil moisture product CS_ESA_SM_2_LAN are level 2 products, which means that the various parameters are provided along-track with a sampling frequency of 1 or 20Hz. A detailed description of the LOTUS products is available in Deliverable D3.1 "Data Product Definition Document detailing each type of product (DPDD)", which is available here.

Table 2: LOTUS products

LOTUS products				
Product description	Product short name	Temporal Coverage	Geographic area	File Size (MB)
L2 Open Ocean product derived from Cryosat-2 data (CPP)	CS_CPP_OO_2_OCE	1st May 2012 – 30th April 2014	N.E. Atlantic	339
			Adriatic sea	41
			Singapore bay	206
L2 Coastal Sea product derived from Cryosat-2 data (CPP)	CS_CPP_CS_2_OCE	1st May 2012 – 30th April 2013	N.E. Atlantic	200
			Adriatic sea	25
L2 Polar Ocean product derived	CS_ESA_PO_2_OCE	1 January	Svalbard	193

from Cryosat-2 data (ESA)		2012- 31 December 2012		
		20 March 2011 15-28 March 2012 20 March 2013-24 April 2013	Arctic tracks	13
L2 River and Lake product derived from Cryosat-2 data (ESA)	CS_ESA_RL_2_LAN	16 July 2010 – 10 July 2014	Denmark	103
		16 July 2010 – 8 July 2014	Thailand Chao Phraya River	65
		1 October 2012 - 9 July 2014	Amazon River	332
		13 October 2012 – 3 July 2014	Brahmaputra River	14
L3 Soil Moisture product derived from Cryosat-2 data (ESA)	CS_ESA_SM_2_LAN	1 January - 31 December 2013	Simpson desert	0.006
		1 January - 31 December 2013	Tenere desert	0.015
		1 January - 31 December 2013	Kalahari desert	0.008

These areas have been chosen based on the CryoSat-2 mode mask. The methodology can however easily be applied to other SAR covered regions and Sentinel-3 data, when these will be available. Some of the main results in terms of ECVs of interest to the climatic community are presented in Section 3

2 European services and projects that could benefit from the LOTUS results

This section lists services and projects that could benefit from the LOTUS results.

2.1 Ocean

- **ESA Climate Change Initiative (CCI)** is a program initiated by ESA. The main focus of the program is global monitoring of essential climate variables. One of the programs is regarding sea level change (http://www.esa-sealevel-cci.org/) and in particular there is a task that focuses on the coastal aspects where LOTUS is relevant.
- **MyOcean Sea Level TAC**.

- **The Joint Technical Commission for Oceanography and Marine Meteorology** (JCOMM) is an intergovernmental body of technical experts (http://www.jcomm.info/).
- **Copernicus Marine Environment Monitoring Service (CMEMS).** The Copernicus Marine Service has been designed by the European Union to respond to issues emerging in the environmental, business and scientific sectors. Using information from both satellite and in situ observations, it provides state-of-the-art analyses and forecasts daily, which offer an unprecedented capability to observe, understand and anticipate marine environment events. The CMEMS provides regular and systematic core reference information on the state of the physical oceans and regional seas. The observations and forecasts produced by the service support all marine applications. The CMEMS Sea Level Thematic Assembly Center is in charge of processing and delivering altimeter products. (http://marine.copernicus.eu/)

2.2 Land

- **The Global Terrestrial Network – Hydrology** (www.gtn-h.info) is a joint project of the Global Climate Observing System (GCOS), the World Meteorological Organization / Climate and Water Department (WMO/CLW), and the Global Terrestrial Observing System (GTOS). The main objective is to make data available from existing network and data resources.
- **Hydrolare** (http://hydrolare.net/) is an international data centre on hydrology of lakes and reservoirs.
- **The International Soil Moisture Network** is an international cooperation to establish and maintain a global in-situ soil moisture database coordinated by the Global Energy and Water Exchanges Project (GEWEX) in cooperation with the Group of Earth Observation (GEO) and the Committee on Earth Observation Satellites (CEOS). It was established to assist validation and enhancement of global satellite observations and land surface models.
- **Hydroweb** (http://ctoh.legos.obs-mip.fr/products/hydroweb) - The first objectives of Hydroweb were to provide users with freely accessible water level time series derived from satellite altimetry over a large number of hydrological targets. The first products were computed over large lakes with Topex/Poseidon data. The number of studied objects rapidly increased as well as the number altimeter missions used in the processing (ERS-2, Envisat, GFO, Jason-1, Jason-2, Saral/AltiKa). It is

now possible to get water level times series for hundreds of lakes and river virtual stations. Moreover, for some selected lakes, Hydroweb also proposes water volume time series based on the combination of water level and surface water area fluctuations. Hydroweb also distributes water equivalent heights time series over most of the large river basins based on gravimetry measurements from GRACE mission.

- **PISTACH** (http://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/coastal-and-hydrological-products.html) - PISTACH mainly consisted in the development of new state-of-the-art dedicated processing algorithms: retracking of the waveforms, wet and dry tropospheric corrections, local models or high resolution global models for topography, geoid, land cover classification, land water mask, data editing. The PISTACH products adopt the same format and structure as Jason-2 standard GDR products to facilitate their appropriation and assessment by expert users, but with additional fields. These products are still presently disseminated on a operational near-real-time basis.
- The **River&Lake** (http://tethys.eaprs.cse.dmu.ac.uk/RiverLake/shared/main) project is very similar to the previous services freely providing users with as many worldwide inland water level time series as possible.
- **DAHITI** (http://dahiti.dgfi.tum.de/en/) is a database of water level time series developed by the Deutsches Geodätisches Forschungsinstitut der Technischen Universität München (DGFI-TUM) based on the same principle as the previous ones.
- **The Global Land component of the COPERNICUS Land Service** (http://land.copernicus.eu/global/) currently entering in an operational phase will aim at providing users with accurate and reliable information in the field of the environment and security, notably inland water level times series computed from Earth Observation Data and especially radar altimetry (with the inclusion of the future Sentinel-3 A and B missions).

3 LOTUS products in terms of Essential Climate Variables

3.1 Sea level

Understanding and monitoring sea level change are essential tasks in the larger climatic perspective. Sea level rise are caused by two effects:

- Adding more water into the ocean e.g. from melting of the ice sheets
- Warming of the oceans, the steric effect.

The Sea level evolution constitutes one of the most important monitoring of the climate change. It is used by the intergovernmental panel on Climate Change (IPCC) in addition to the surface temperature evolution, the greenhouse gas concentration evolution and the CO2 emissions (See Figure 14 of the last report: https://www.ipcc.ch/report/graphics/index.php?t=Assessment%20Reports&r=AR5%20-%20Synthesis%20Report&f=SPM).

Satellite altimetry captures changes in the sea level and hence measures both effects. Satellite altimetry was developed to measure the sea level, and the period of available data spans more than 30 years.

3.2 Open and coastal ocean

The smaller antenna footprint of the SIRAL altimeter in SAR mode makes it possible to obtain more accurate estimates of the sea level closer to the coast – especially when the track is perpendicular to the coastline. Although the effect of land contamination in the waveform is greatly reduced it is not removed completely. Hence novel processing algorithms have been developed in order to further reduce the effect of land contamination in the waveform to obtain more accurate water level estimates closer to the coast. A detailed description of these algorithms is found in Deliverable 1.3 "SAR mode for Ocean Algorithms Theoretical Basis Document" (available by clicking here). For Open and coastal oceans sea level estimates are available in the following test areas; North East Atlantic, Adriatic Sea, and Singapore bay.

The increasing interest of SAR mode altimetry, especially in coastal areas, is linked to the higher resolving measurement capability in the direction of the platform velocity, i.e. along-track direction. The improved resolution is a consequence of the delay-Doppler processing of the radar echoes. The along-track resolution reaches values typically around 250 to 300 meters (R. K. Raney, Resolution and Precision), which represents a remarkable improvement in comparison to the several kilometres currently achieved with conventional altimetry.

Two major consequences of such improvements are first, the sea level monitoring at global scale is significantly improved, and therefore the estimation of sea level rise can be better estimated, and secondly, the sea level estimation close to coastal areas has been improved and provide interesting results for coastal monitoring where the effect of climate change is the most visible. The improvement of sea level estimation near the coasts can clearly contribute to provide better estimates of sea level change.

3.3 Polar Ocean

SAR altimetry is a huge step forward for Polar Ocean sea level research. This is particularly due to the enhancement in along-track resolution (300 meters), as well as the smaller footprint in the SAR processing, and the improved capabilities using the SAR stack information in determining the leads in the sea ice.

With the use of SAR altimetry we are for the first time able to provide a sea level estimate within the leads of the sea ice. The accurate information on sea level can directly be used to determine information about the free-board of the ice and hence the amount of sea ice and the thickness of the sea ice. SAR altimetry can capture and measure sea level in small leads in the sea ice and hence provide a much better spatial pattern of sea level variations.

An important parameter to climate research is the mean sea surface (MSS) and more importantly the derived quantity – the mean dynamic topography (MDT). The MDT is the difference between the mean sea surface and the geoid. The geoid is the surface that the ocean would be if they were at rest and the MSS is the actual mean of the real ocean surface reflecting the ocean currents wind and pressure.

Surface geostrophic currents carrying water and heat in and out of the Arctic Ocean are associated with the slope of the MDT. With the development in both SAR altimetry and geoid modelling using the European GOCE satellite it has for the first time been possible to derive an accurate and reliable MDT from satellites.

This is illustrated in Figure 1 where two versions of the DTU MDT are shown. One without the Cryosat-2 SAR altimetry (DTU10MDT to the left) and one derived with the use of Cryosat-2 SAR altimetry (DTU13MDT to the right). The difference in the North Atlantic is very small as expected. However, the difference in the interior of the Arctic Ocean is significant.

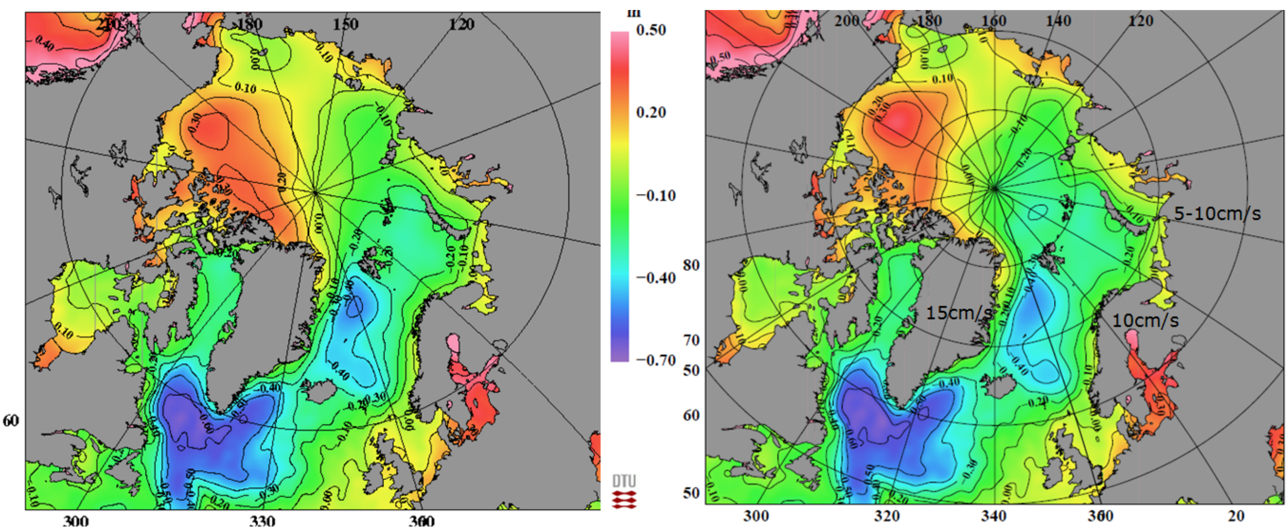

Figure 1: The Mean Dynamic Topography in the Arctic Ocean. The left figure is derived using DTU10MSS prior to the availability of Cryosat-2 SAR altimetry and the right figure if DTU13MSS derived with the use of Cryosat-2 SAR altimetry. The difference in the North Atlantic is very small. However the difference in the interior of the Arctic Ocean is significant.

That DTU13MDT is far more realistic than DTU10, in particularly the Canadian basin where it shows the circulation of the Beaufort Gyre more accurately, can be seen from Figure 2. Figure 2 shows the comparison between the satellite derived DTU13MDT (top) and MDTs from three different ocean models (bottom). Shown below the DTU13MDT are the German ECCO (http://www.ecco-group.org/), the Miami Isopycnic Coordinate Ocean Model (MICOM, http://rda.ucar.edu/datasets/ds287.1/), and University of Washington PIO (http://psc.apl.uw.edu/) bottom left to right) hydrodynamic MDT for visual comparison. The same colour scale is used for all plots in order to illustrate the similarity between the synthetic MDT from satellite and the hydrodynamic MDTs. The averaging periods for the various models are not identical being 1993-2003 for GECCO; 1995-2005 for MICOM_F04 and 2003-2006 for the PIO model. Consequently, a detailed comparison is hard to perform. Also different offsets have been added to the different models. However,

Figure 2 visually illustrates that the agreement among hydrodynamic models is the same as the agreement between hydrodynamic and satellite derived models. Satellite derived models can therefore for the first time be used to validate hydrodynamic models in the Arctic and vice versa.

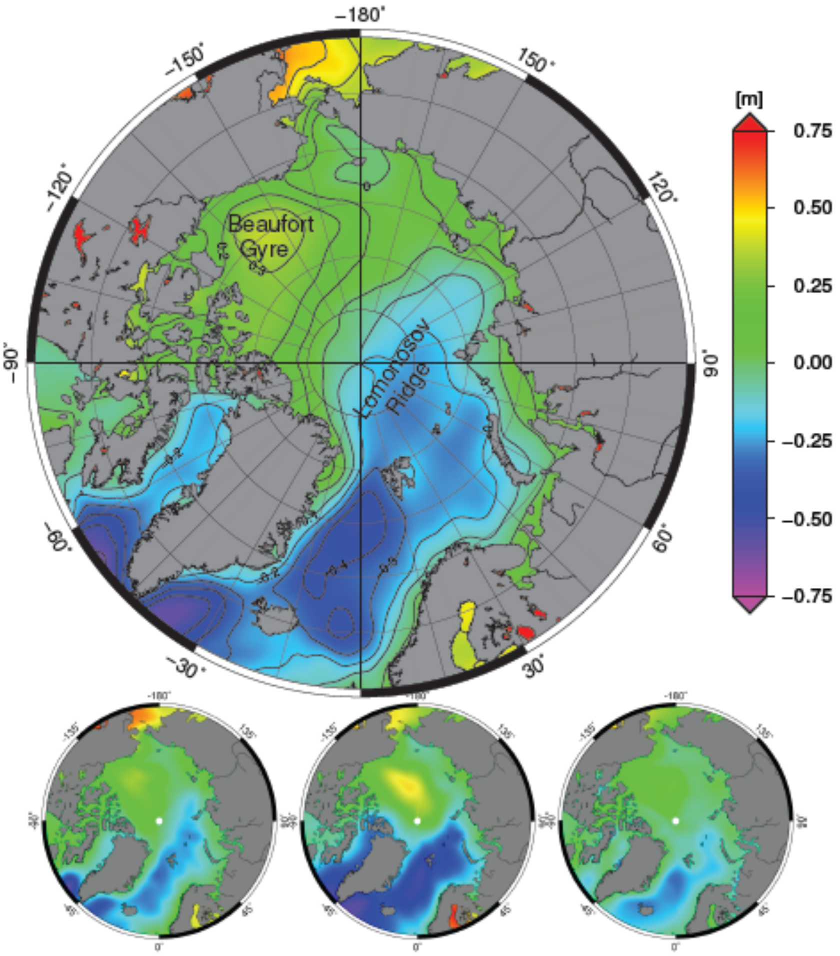

Figure 2: The DTU13MDT (height in meters) for the Arctic Ocean (upper figure). The lower figure shows the MDT computed from 3 years average of the GECCO, the MICOM, and University of Washington PIO (bottom left to right) hydrodynamic MDT.

For climate research it is of fundamental importance to maintain as long a time-record for the Arctic Ocean as possible from satellite. Figure 3 illustrates the 25 years sea level time series of the Arctic Ocean from the European satellites ERS-1, ERS-2, ENVISAT, Cryosat-2, and SENTINEL-3 in the future. It demonstrates that on a 25-year timescale the Arctic Ocean within 65N to 82N increases by roughly 2.2 mm/year, which is of the same order as the global sea level rise.

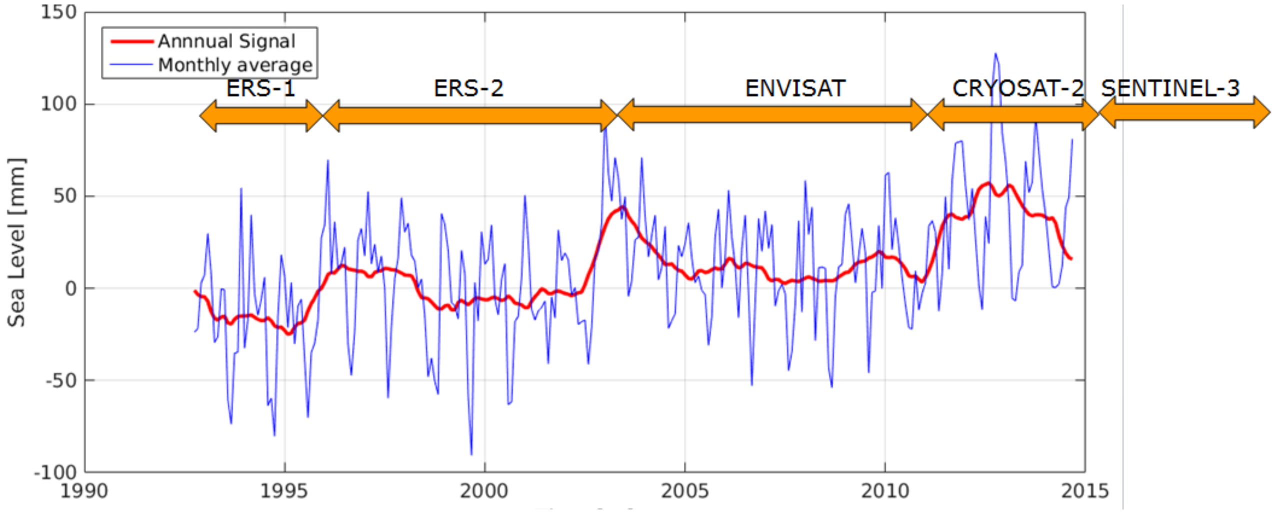

Figure 3: The 25 years sea level time series (65N to 82N) of the Arctic Ocean from the European satellites ERS-1, ERS-2, ENVISAT, Cryosat-2 and SENTINEL-3 in the future.

Having an accurate MSS determined from satellite altimetry enables better studies of sea ice freeboard in the Arctic. Figure 4 illustrates the sea ice freeboard in the Arctic Ocean from Cryosat-2 SAR altimetry referenced to the DTU13MSS partly developed within the LOTUS project. The figure clearly shows the minimum in sea ice freeboard in 2012 and 2013 and a recovery of sea-ice freeboard in 2014.

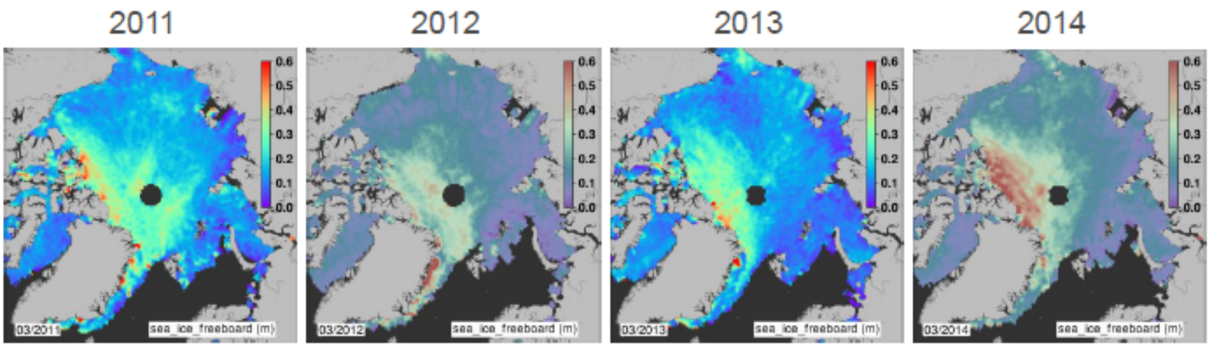

Figure 4: Sea ice freeboard for the Arctic Ocean derived from the DTU13 MSS.

3.4 Sea state

The term sea state referrers to the general condition of the free surface of the oceans including waves, wind, and swell. According to GCOS the sea state can provide valuable climatic information regarding air-sea exchanges and changes in the marine environment e.g. winds, storms, air-sea fluxes and extreme events. Satellite altimetry provides the significant wave height and wind speed on a global scale.

The CMEMS service that has started in may 2015 now offers wave products that are provided by the Monitoring and Forecasting Center (modelling centres). Nevertheless, these centres will need wave observations coming from in-situ and remote sensing for assimilation and validation purpose. They are currently discussion to set up a wave service based on the remote-sensing data (altimetry (Sentinel-3) and Radar (Sentinel-1)).

3.4.1 Services by DHI of sea states to European institutions and industries

DHI is basing its metocean services to European and international offshore customers on a combination of advanced numerical model, high-resolution satellite earth observations and on-site observations. Traditionally, DHI's GMES offshore services have relied on numerical models supplemented with sporadic observations from in-situ buoys or offshore platforms, being tied to a few single locations and also often very limited in duration. The LOTUS project has enabled development of technologies enabling access to high-resolution earth observations from e.g. CryoSat-2 or Sentinel and technologies for data fusion into DHI's MIKE models. The general advantage of this approach is the combination of global coverage accurate observations of sea states with intermittent coverage with numerical models that provide a continuous coverage. The combined GMES product therefore inherits the best from the two methods providing improved value of the service. This is especially true in open waters or inaccessible areas, where no ground truth data exist. These GMES services and technologies are important as a basis for assessment and planning of climate change adaptation. A general experience from the work has been acknowledgement of the superior features available with SAR as compared to previous LRM observations. For near-coastal services this is very important to have access to high resolution data close to the coast (see Figure 5).

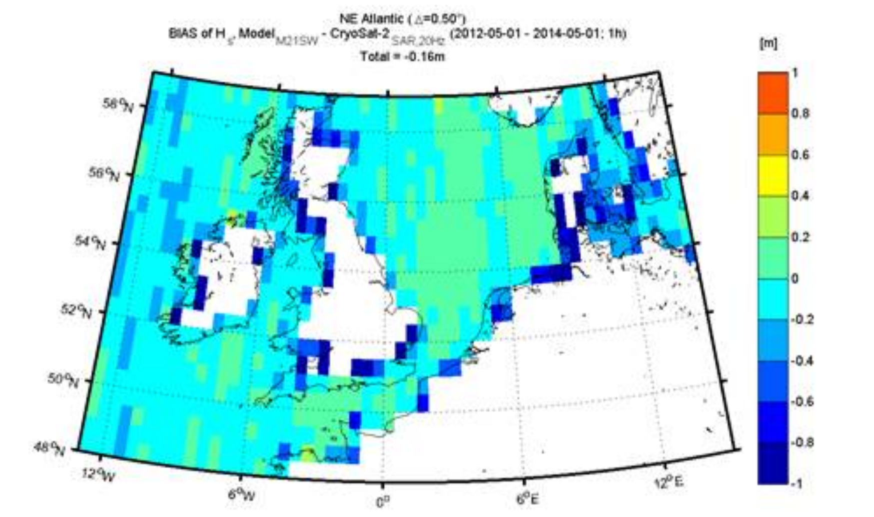

Figure 5: Example of bias between CryoSat-2 estimated significant wave height and MIKE 21 Spectral Wave model of the North Sea during 2012-2014.

One example of a GMES climate change service is a map showing wave sea states for various climate change projections. Such information is invaluable for planning of offshore activities and for design of critical marine infrastructure. The development of such maps critically relies on an accurate and high resolution founding dataset that ensures the underlying model projections are representing the physical environment realistically.

During the LOTUS period DHI has developed GMES services of this kind to a number of projects within offshore wind energy, within marine renewable energy as wave and tidal energy, the offshore oil and gas sector, maritime services and for activities related to marine spatial planning.

As part of DHI's marine GMES services we have developed an on-line data portal, where climate related data are accessible for the marine community. The data portal forms also a part of DHI's professional service to the European industries and institutions. The DHI's GMES Example of publications describing Examples of DHI's GMES services are described In Grode et al., (2014) and Bruning and Precht, (2014)

In Table 3 is shown a list of recent offshore energy projects where DHI's GMES services have been relevant

Table 3: Projects where the GMES services from DHI have been relevant.

Project	Client
Q10 Offshore Wind Farm, the Netherlands. Monitoring of seabirds on the Dutch continental shelf.	ENECO, the Netherlands
Pentland Firth and Orkney Waters. Modeling of wave and tidal resources.	Crown Estate MMEA project
Clearwater. Installation of first full-scale tidal farm.	European Union with partners Atlantis, Royal Haskoning ans University of Edinburg
Amrumbank West Offshore Wind Farm, Germany. Monitoring of waves and currents during installation of foundations and turbines.	E.ON Kraftwerke GmbH, Germany
Rampion Offshore Wind Farm, UK. Metocean study for foundation design.	LICenergy UK Ltd, UK on behalf E.ON UK Renewables
Saint Nazaire Offshore Wind Farm, France. Metocean study for detailed design.	Eolien Maritime France (EMF)
Courseulles-sur-Mer Offshore Wind Farm, France. Metocean study for detailed design.	Eolien Maritime France (EMF)
Kriegers Flak Offshore Wind Farm, Denmark. Baseline investigations and environmental impact assessments (EIA) of marine mammals and birds.	Niras A/S, Denmark on behalf of Energinet.dk, Denmark
Three coastal offshore wind farms in Danish waters, Denmark. Baseline and impacts assessments on birds and marine mammals involving aerial surveys, telemetry, radar and acoustic investigation.	Rambøll, Denmark on behalf of Energinet.dk, Denmark

3.5 Lake and river levels

The water level of rivers and lakes is an important climatic parameter in the sense that it represents the hydrological balance (precipitation and evaporation) of the surrounding area. Especially closed-basin lakes are sensitive to the changes in the relationship between precipitation and evaporation, and therefore serve as markers of the regional climate. GCOS has constructed a prioritized list of lakes that need to be monitored in order to assess the state of the climate. Ideally the lake level should be measured on a daily or at least on a monthly basis with a vertical resolution of 10 cm (GCOS 2010).

Water levels of inland water bodies from radar satellite altimetry have been derived for more than 20 years, and have proven to be a valuable supplement to in-situ station data, which are declining in number on a global scale. Hence, satellite altimetry can provide continuous time series of the world's rivers and lakes, which is invaluable in terms of climate monitoring.

In the LOTUS project the primary focus has been on SAR altimetry, for which four test areas have been selected: Denmark, Thailand, Brahmaputra River and Amazon River. Due to the relatively long repeat period of CryoSat-2, a significantly larger amount of water bodies are monitored. The number of crossings depends on the size of the water body in the east-west direction and the latitude. Hence, small lakes may only be visited a few times per year. Below is a presentation of some of the results obtained in the LOTUS project.

3.5.1 Example of lake levels over a small lake

The first example (Nielsen, et al., 2015) demonstrates the better precision that can be obtained with SAR altimetry due to the smaller antenna footprint. The Danish lake Arresø (for location see Figure 6) has a surface area of 40 km2 and is surrounded by relatively flat terrain. Due to its smaller surface area it is only visited by CryoSat-2 four times per year. For this lake in-situ data is available from the Danish Nature Agency, which makes it possible to validate the satellite-based water levels. To investigate the performance of SAR altimetry compared to conventional altimetry, Envisat-based water levels have been used. Figure 7 displays the altimetry-based water level time series together with in-situ data.

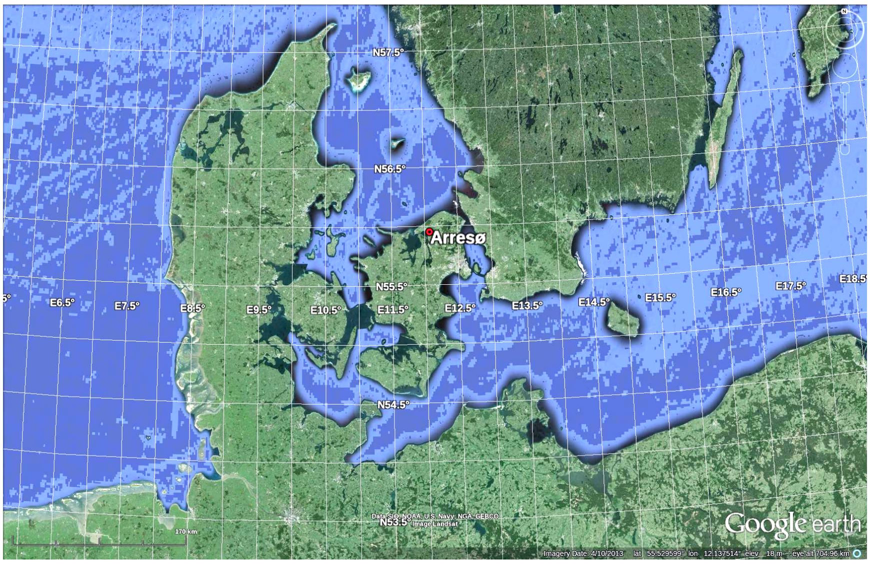

Figure 6: Location of Arresø

The water level time series shown in Figure 7 and Figure 8 demonstrates the higher quality of the SAR data. The CryoSat-2 data shows a clear improvement in the stability of the derived water levels and we are now able to measure water level variations at the decimetre level (at least in areas with minor topography). The CryoSat-2 data has been compared with in-situ data for validation. After a bias correction to account for the different height systems, the CryoSat-2 based water levels fits the in-situ data within a few centimetres.

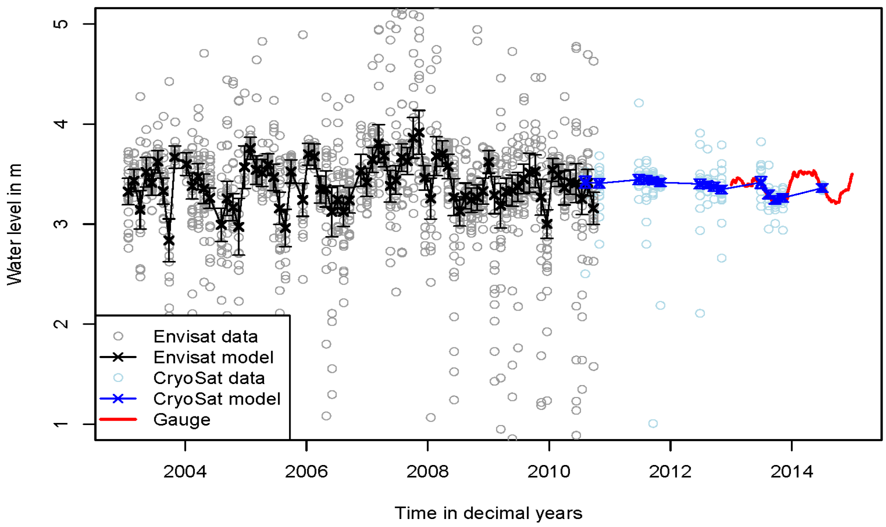

Figure 7: Water level time series of Arresø, Denmark. The black and blue crosses demonstrate the result based on Envisat and CryoSat-2, respectively. The red line is in situ data.

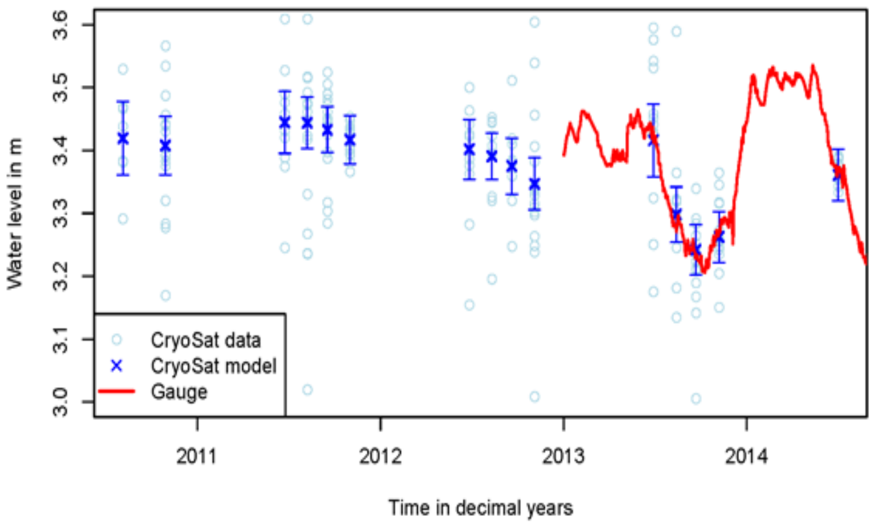

Figure 8: Same as previous figure but a zoom in on the CryoSat-2 and in situ data part.

3.5.2 Example of virtual stations over the Brahmaputra River

The drifting track pattern of CryoSat-2 makes it more challenging to obtain time series of the river level. Since the tracks will cross the river at different locations at part of the observed water level is due to variations in the terrain. The following example (Villadsen et al., 2015) demonstrates that time series can be obtained at virtual station by applying a simple linear correction for the topography. Time series were obtained for all three modes of the SIRAL altimeter carried by CryoSat-2, however, only the results from LRM and SARIn are shown below in Figure 9. The study showed that CryoSat-2 was able to capture the same annual signals as Envisat despite the uncertainties introduced by the geodetic orbit.

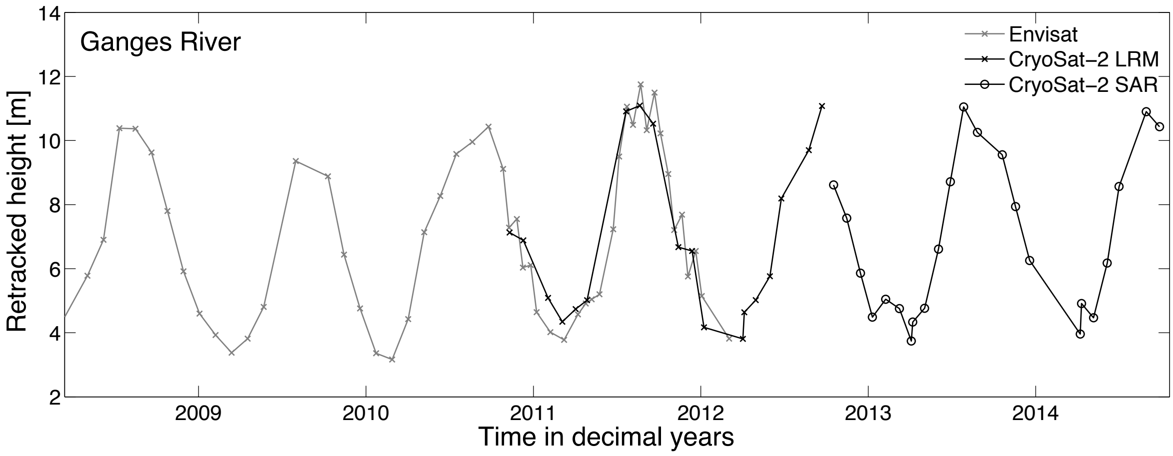

Figure 9: Water level time series obtained over the Ganges River for CryoSat-2 and Envisat data.

3.5.3 Altimetry for inland Water (AltWater)

The methodology described in Nielsen et al., (2015) has been applied to various lakes on a global scale. The results of this forms the basis of a new open service called "Altimetry for inland Water" (AltWater), which is available from the web page http://altwater.dtu.space/. Currently the service is only based on CryoSat-2 data, but other missions are expected to be added. From the web page along-track water levels and time series of lake levels can be downloaded directly. Figure 10 shows a map of the available targets.

Figure 10: Locations of available data at AltWater

3.5.4 River discharge

Freshwater discharge is an important parameter of the global hydrological cycle and therefore plays a key role in the climate system. Although there is a growing need for better observations of river discharge at a global level, the number of in situ gauge stations continues a decrease – especially in remote areas. In addition, information about fresh water resources is often restricted.

Satellite altimetry has been used for hydrological investigations for more than 20 years, and has proven to be a valuable addition to in situ data. River discharge estimates can be derived from altimetric water levels by using rating curves, which describe the relationship between discharge and the water level for a given location on a river. In this way, satellite altimetry can contribute to river monitoring, water resources management, and climate change detection.

3.6 Soil moisture

According to GCOS soil moisture has an important influence on land-atmosphere feedbacks.

Soil surface moisture is a key climate variable, vital for a range of applications, including numerical weather predictions, flood and drought prediction and monitoring, water resource management, agriculture and epidemiological forecasting. In-situ data availability is sporadic and localised in spatial extent (Dorigo et al., 2013): thus remote sensing techniques have a key role in global and regional monitoring of this parameter. Both active and passive sensors are used to derive soil moisture (e.g. Liu et al., 2011). The key importance of this variable is underlined by the first two dedicated satellite missions, both currently operational; the ESA SMOS mission (Mecklenburg et.al., 2012) and the NASA SWOT mission (Panciera et al., 2014) .

One constraint on existing global remote sensing datasets is the pixel size, typically 0.25 degrees (e.g. Dorigo, 2013). Soil moisture from satellite altimetry offers finer spatial sampling along-track and a more precise measurement capability in arid and semi-arid terrain, where other techniques encounter difficulties. The new enhanced DRy EArth ModelS (DREAMS) developed in the LOTUS project now allow detailed estimates from prior altimeter missions to be made; these data are now being processed to yield time series. In parallel with this activity, DREAM creation is being trialled over wetter areas to extend the remit of this new technique. The role of altimeter-derived soil moisture is seen as complementary to other remote sensing datasets, and as a bridge between the detailed local scale in-situ measurements and the generalised (0.25 degree) scale global remote sensed datasets.

Key results from the LOTUS work are shown here for track-averaged products. The Kalahari augmented DREAM is shown together with the Jason2 validation track locations in Figure 11(a), with the three tracks selected for validation labelled A-C. Figure 11(b) shows the time series of soil moisture measurements from these Jason2 tracks, plotted together with the spatially disparate CryoSat-2 estimates. The Jason2 estimates are seen to ’bracket’ the CryoSat-2 CSME results, showing good agreement.

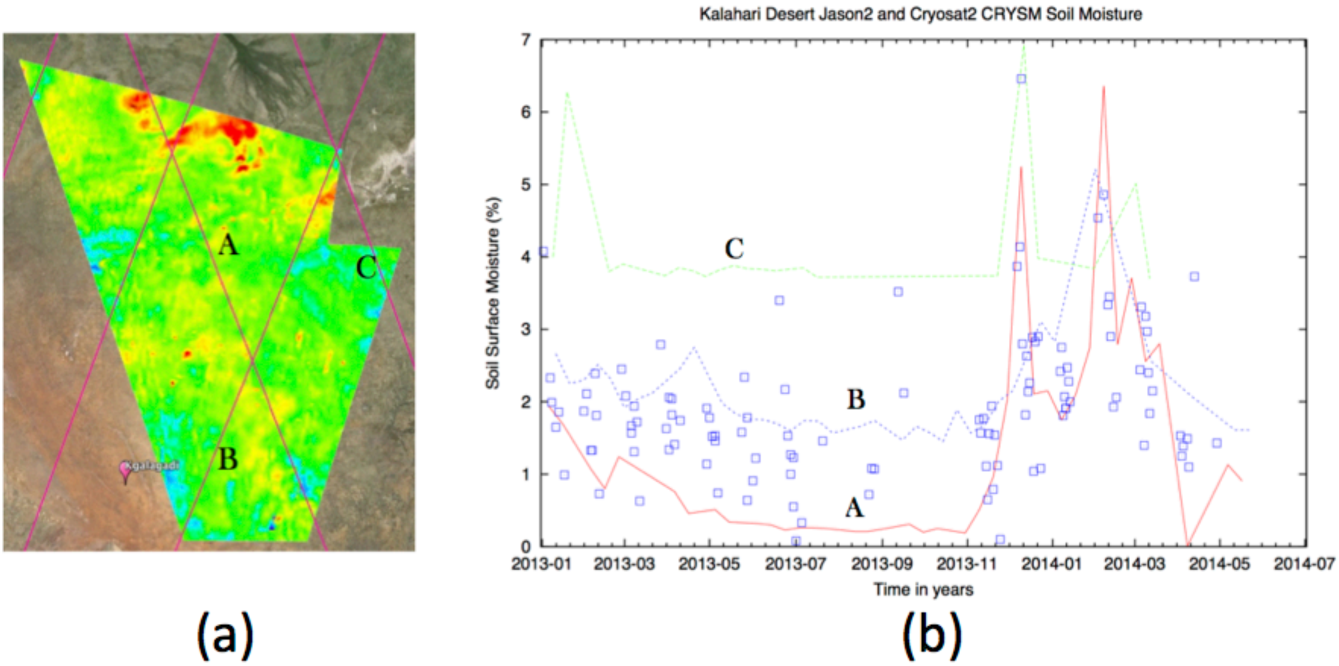

Figure 11: Track based soil moisture measurements over the Kalahari Desert from CryoSat-2 and Jason-2 using Cryosat-2 enhanced DREAM

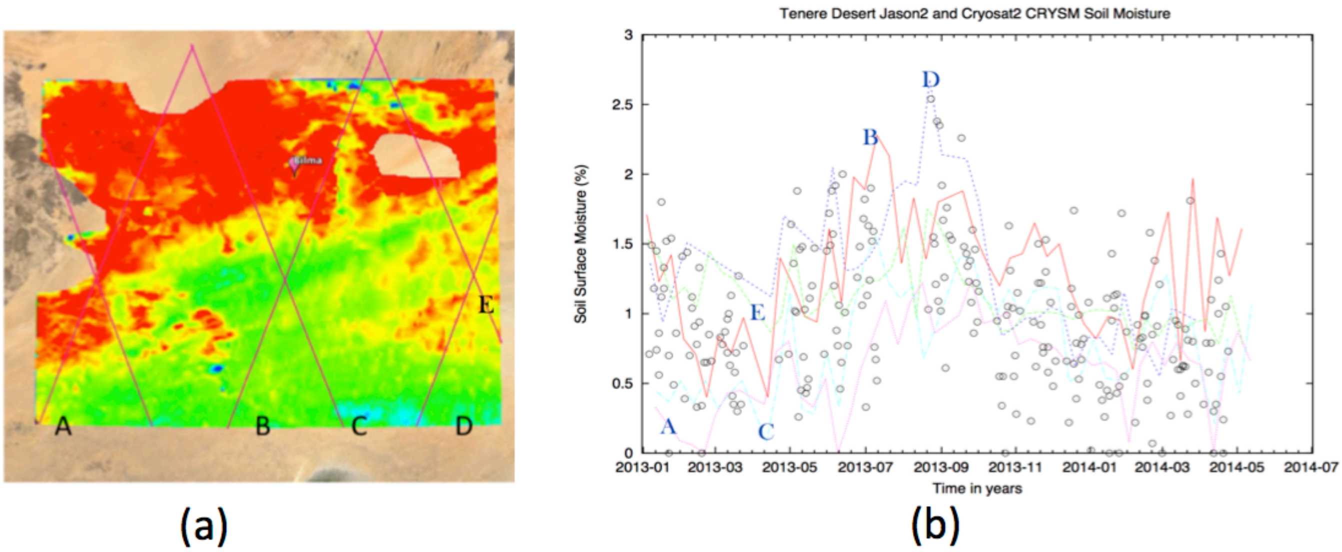

Figure 12: Track based soil moisture estimates over the Tenere desert from CryoSat-2 and Jason-2 using CryoSat-2 enhanced DREAM

Figure 12 shows the corresponding results for the Tenere Desert. Again, the Jason-2 estimates agree well with the spatially disparate CryoSat-2 soil moisture estimates.

The track average constraint has now been relaxed due to the very good DREAM performance, and estimates are being made on a spatial scale of 18" – 27" along-track. One key outcome of this work is the building of enhanced DREAMS to allow retrieval of soil moisture from altimeter arcs without a repeat cycle (this precludes filtering out residual paleo-hydrology signatures). The successful retrieval of soil moisture estimates from Jason2 over all three test deserts with no repeat arc filtering applied confirms the excellent quality of these models, and illustrates the potential of this novel technique for soil moisture retrieval.

3.7 Snow depth

The estimation of snow depth using altimeter is not mature enough yet to develop operational products. But, through the investigation, interesting results show a trend in the data that could allow snow depth estimation. However, such improvements can provide snow coverage information that could show the evolution of snowfall in mountain areas and others. This evolution is very representative of the current changes in the climate. Additionally, the products developed could be used into models for different purpose in combination with auxiliary parameters, in particular, to estimate the water content in (natural and artificial) storage areas.

4 Summary

When considering the outcome of the LOTUS project it is clear that SAR altimetry has made a significant impact on the derived results. In terms of sea level the estimates are in general of higher quality. The higher resolution in the along-track direction makes it possible to achieve valuable sea level estimates closer the coasts. In the Polar Ocean the availability of SAR data from CryoSat-2 has resulted in significantly more useful data from leads in the sea ice, which was not possible with conventional Low-resolution data. The better sea level estimates further results in better derived products such as the MSS and the MDT.

For continental water we find similar improvement in the derived water levels. In areas of low topography we are able to observe changes in the water level below the decimetre level. It has further been demonstrated the soil moisture successfully can be derived from satellite altimetry and that these products complement available products in terms of a finer spatial resolution. Estimation of snow depth from satellite altimetry is still at a premature state, however, the results obtained in the LOTUS show promising results.

As this report clearly states, the outcome of LOTUS project can contribute to the estimation and monitoring of several essential climate variable.

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