ADVANCES ON COASTAL EROSION ASSESSMENT FROM SATELLITE EARTH OBSERVATIONS: EXPLORING THE USE OF SENTINEL PRODUCTS ALONG WITH VERY HIGH RESOLUTION SENSORS

Paula Gomes da Silva[1], Anne-Laure Beck[2], Jara Martinez Sanchez[1],
Raul Medina Santamaria[1], Martin Jones[3], Amine Taji[2], and all the members
of the "Coastal Change" group within BGS, GIS, IHC, Arctus, UCAR, and IGNFI
[1] Environmental Hydraulics Institute "IH Cantabria", Universidad de Cantabria,
C/Isabel Torres 15, 39011, Santander, Spain
[2] Argans France, 260 Route du Pin Montard, 06410 Biot
[3] Argans UK, 1 Davy Road, Plymouth Science Park, Derriford, Plymouth, PL6 8BX UK

Abstract – This work proposes the use of automatic co-registered satellite images to obtain large, high frequency and highly accurate shoreline time series. Very high-resolution images are used to co-register Landsat and Sentinel-2 images to reach a vertical and horizontal spatial accuracy within 3 m. Satellite derived shorelines presented positioning errors lower than mission pixel's resolution. A discussion is presented on the applicability of those shorelines through an application to Tordera Delta (Spain).

Introduction

Climate Change and human activity are likely to have an increasingly dramatic effect on coastal zones. The analysis of the effects on the coast requires better knowledge and more regular and efficient monitoring in order to manage and mitigate impacts of the changing coastal environment. Although in-situ measurements are highly efficient on capturing coastal parameters and features at a given time, the cost of continuous acquisition campaigns is dissuasive. Earth Observations provide wide spatial coverage over a large temporal scale. However, the lack of geolocation accuracy (i.e. the position of details and features usually visible on HR satellite imagery) challenges the conclusions of most academic studies. Spatial accuracy is defined for this study as the conformity in location between the different earth observations and a reference, in a way that an object in a set of images is located at the same location, while the precision is the spatial shift of the objects from what is actually observed in situ. The specific dynamics linked with the coastal environment imply additional constraints due to the different scales of the studied phenomena. Coastal processes, which impact the coastal morphology, are characterized by high temporal variability, ranging from a few hours or days (e.g. storms or artificial beach nourishments) to years or even decades (e.g. Metonic cycles and sea level rise).

The reduced spatial and time scale of coastal changes makes high spatial accuracy necessary and this is under constant improvement (e.g. [7]). The application of the geo-location method, for example, greatly improves the spatial accuracy and allows features inter-location around a few meters accuracy, although such procedure can be time consuming. While the use of automatic methods to obtain geo-located images can be very effective, so far it has not

FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)
Paula Gomes da Silva, Anne-Laure Beck, Jara Martinez Sanchez, Raul Medina Santamaria, Martin Jones, Amine Taji, *Advances on coastal erosion assessment from satellite earth observations: exploring the use of Sentinel products along with very high resolution sensors,* pp. 412-421, DOI 10.36253/978-88-5518-147-1.41

been tested with the focus on detecting coastal changes (e.g. [11]). On the other hand, it is the temporal variability that challenges the most coastal analysis. While there is an evident interest on obtaining long, high frequency and high accurate time series from EO products, building a stable statistical data set from them is a challenge. [14], for example, demonstrated that current available satellite data from optical sensors are suitable to represent shoreline changes in inter-annual to decadal time scales, but could not explain sub-annual variations.

This study proposes the use of automatic co-registered satellite images to obtain long, high frequency and high accurate shoreline time-series. These Satellite Derived Shorelines (SDSL) are used to compose long and high frequency time series. The applicability of those products is demonstrated with a study case at Malgrat beach (Tordera Delta - Spain) in which shoreline variation is assessed in different time-scales.

Materials and Methods

Malgrat beach is located southward of Tordera river mouth (forming the Tordera Delta) in the northern coast of Cataluña (Spain – Figure 1a). The longshore sediment transport occurs predominantly from NE to SW in Cantaluña coast. Over years, the water capture along the river basin and the construction of port structures on the coast northwards of Tordera River (e.g. Port of Blanes), have led to a considerable reduction of the sediment input and have resulted in intense erosion of Malgrat beach ([9], [2]). In the 90's, a considerable amount of sand was recovered from the shallows in front of the mouth of the Tordera river in order to re-nourish beaches in Cataluña. The resultant trough in the sea floor is now a sink to the sediment and makes redistribution of the sand along the coast difficult.

In the past decades, this coast suffered a maximum shoreline retreat of about 120 m (Figure 1b and Figure 1c), with erosion rates reaching -3.8 m/year ([5]). Rapid retreat of about 25 m can also result from single storm events ([6]), a value that can be enhanced due to changes in wave conditions derived from Climate Change ([10]). These issues led to the need for numerous interventions, including soft stabilization and nourishment projects (Figure 2). Nonetheless, these initiatives did not prevent the erosion occurring, and a large urban area has been lost due to shoreline retreat.

The historical shoreline variation at Malgrat beach is characterized by a sequence of retreats due to storm induced erosion events alternated with punctual human-induced progradation (Figure 2). In 2008, for example, the San Esteve Storm, desolated Cataluña coast and resulted in significant shoreline retreat at Tordera Delta [4]. In May 2015, the continuous erosion required the authorities to carry out a project to restore and protect the beach, with the construction of geotextile groins and the dumping of 112 000 m^3 of sand (Figure 2b). In the following November, a storm event hit the Cataluña coast and a significant amount of the sand dumped on the beach in the previous months was lost. In January 2017, a sequence of storm events again made the shoreline retreat (Figure 2c), reaching a maximum on 19th-23rd of that month. The most recent event with significant magnitude occurred on January 2020, a weather event named the Gloria Storm, which damaged urban areas near the coast due to severe wave and storm surge conditions. As part of the plan to monitor the area, in situ measurements were taken, for example, on November 11th 2015, and May 2017. All the occurrences outlined above make this area an interesting site for EO application in different time scales, since change due to long-, mid- and short-term processes take place in it.

Figure 1 - Location of the study case site (a), Malgrat beach (Spain) and situation of the coast in 2004 (b) and 2018 (c). The yellow polygon indicates the coastal area lost due to erosion problems along the 14 years.

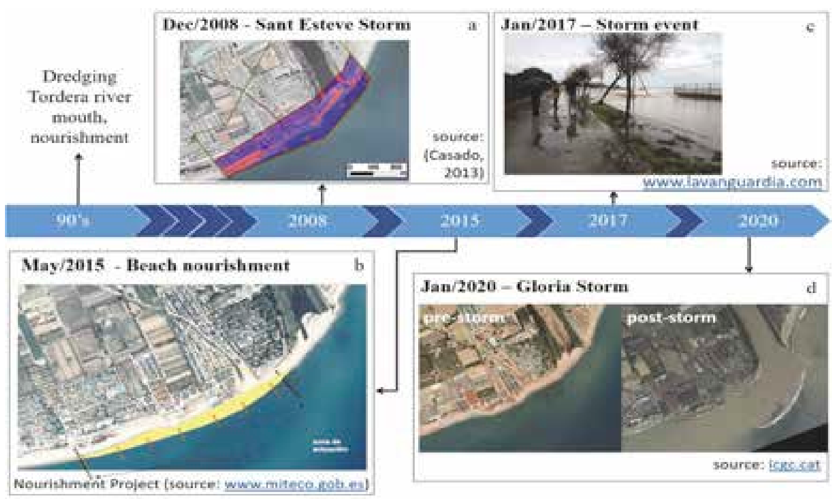

Figure 2 - Timeline of punctual actions/events that took to espressive shoreline variability of Malgrat beach. a) 2008: results from LiDAR analysis from [8] where red colors indicate sediment lost areas due to Sant Esteve Storm. b) 2015: nourishment project carried out to restore the beach. c) 2017: effects of the storm registered by local news. d) 2020: aerial photos taken of previous and posterior to the Gloria Storm.

For this study, we use a combination of several optical sensors to increase the number of observations over our area of interest and to obtain longer time series. Landsat 5 & 8 and Sentinel-2 data were combined to cover a wider time range (1994-2018) and to increase the number of observations over a same site. Very High Resolution (VHR) imagery is used to co-register the Sentinel-2 and Landsat data. Those VHR are obtained from commercial missions. Maxar's WorldView 2 data were used for the co-registration of HR images over Tordera area. Table 1 details the specification of the different missions used.

Table 1 - EO missions and their specifications with optical sensors.

Satellite constellation	sensor & bands (optical)	pixel resolution of L1 products	Revisit time	Years active
Landsat 5	0.45÷0.52 μm, 0.52 ÷ 0.60 μm, 0.63 ÷ 0.69 μm, 0.77 ÷ 0.90 μm	30 m		
Landsat 8 (OLI)	0.503 ÷ 0.676 μm	15 m	16 days	2013 –
	0.435 ÷ 0.451μm, 0.452 ÷ 0.512 μm, 0.533 ÷ 0.590 μm, 0.636 ÷ 0.673 μm, 0.851 ÷ 0.879 μm	30 m		
Sentinel-2 A & B /MSI	448÷546 nm, 537÷583 nm, 645÷683 nm, 762÷908 nm	10 m	5 days	2015 –
	604÷723 nm, 731÷749 nm, 768÷796 nm	20 m		
	430÷467 nm, 932÷958 nm	60 m		
WV-2	450÷800 nm	0.46 m	1 day	2009 –
	400÷450nm, 450÷510 nm, 510÷580 nm, 585÷625 nm, 630÷690nm, 705÷745 nm, 770÷895 nm, 860÷1040 nm	2 m		

Optical observations were used to compose large and high frequency time series of shorelines. For that purpose, the waterlines (the observed instance in time of the boundary between land and sea) need to be extracted with a very high location accuracy. However, from one sensor to another and from one acquisition to another, we observe a spatial shift (i.e. EO observations have errors and uncertainties that lead to different positioning). For Landsat-8 the geo-location accuracy is around 30 m, while for Sentinel-2 L1C (without ground control points) the accuracy is around 10 m at 2σ confidence level [3]. To correct the displacement between images, VHR imagery with high location accuracy, are used as a master to co-registered observations of the different sensors. VHR were pre-processed to correct and remove the effect of haze vapor, then, the ASORICS (Automated and Robust Open-Source Image Co-Registration Software) [11] was used to apply the Fourier shift theorem in order to determine precise X/Y offset at a given geographical position through phase correlation. This process can only be applied for single band images with same spatial resolution and, ideally, similar pixel intensity. This criterion is not fulfilled when dealing with multi-temporal and multi-spectral data from different sensors, therefore, we combined a pure phase correlation approach with additional processing and evaluation modules.

Once the satellite images were geo-located, waterlines were obtained and transformed to datum (Mean Seal Level REDMAR – *Red de Mareógrafos de Puertos del*

Estado) based shorelines using the beach slope and sea water level (observed sea level at the coast including tide, surge and wave data). SDSLs were validated for the study site using data from in-situ measurements. SDSLs closest to measurement days (maximum ±7 days) were compared with in-situ shorelines at transects displaced every 15 m along the coast. The cross-shore distance between in-situ measured data and the SDSL was used as an error measure to calculate the Mean Absolute Error (MAE) and the Brier Skill Score (BSS, [12]). Perfect agreement gives a BSS of 1, whereas observing the baseline condition (first SDSL from 1994) gives a score of 0. Additionally, shoreline variations were compared to results presented in previous studies.

A detailed analysis of shoreline variation on Malgrat beach was carried out to show the potential of co-registered SDSL time series to assess coastal changes in different timescales. A total of 184 shorelines from 1994 to 2018 were used to assess short-, medium- and long-term shoreline variation. Long-term trends in shoreline changes were estimated using the Digital Shoreline Analysis System, DSAS [13]. Shoreline evolution was assessed to verify the changes in trends of Tordera Delta coast. Short term application was assessed through the analysis of the shoreline movement in two events: i) a nourishment event carried out in May 2015 and the subsequent storm erosion in November 2015, and ii) a sequence of storms on January 2017 (see list of events in Figure 2).

Results

The co-registration process, performed on all public images, allows the relocation and the perfect overlap from one EO image within the same tile to another. In 90 % of cases, the co-registered images showed horizontal and vertical shifts below 3 m in comparison to VHR. In other words, all images are repeated within 3m of their true location.

In-situ measurements and SDSL from November 2015 are used for validation. The shorelines are presented in Figure 3, as well as the baseline used to calculate the BSS. Here, the baseline was taken as the earliest SDSL available (from 1994). The MAE between both shorelines was equal to 21 m, falling within the range of the horizontal accuracy of Landsat 8, which is typically 30 m. BSS was equal to 0.96 which indicates good agreement between measured and satellite data and the ability to represent long-term variations. Shoreline variation rate, calculated using SDSLs, also agrees with values presented before. [1], used high-resolution aerial photographs and obtained an average erosion tendency of –4.68 m/year between 1995 and 2009 in the coast southward of Tordera river moth, a value similar to the one obtained here using the SDSL (-4.79 m/year) for the same period.

Discussion

The co-registration process results in images with high spatial accuracy, however the global quality depends on the number of ground points that the processor is able to use to adjust the images. Points selection, which is linked with weather conditions such as cloud cover and type of land use (points extraction is more reliable over man-made structures, over build-up areas than over natural environment such as forest or over large crops field) is a vital step in establishing the process.

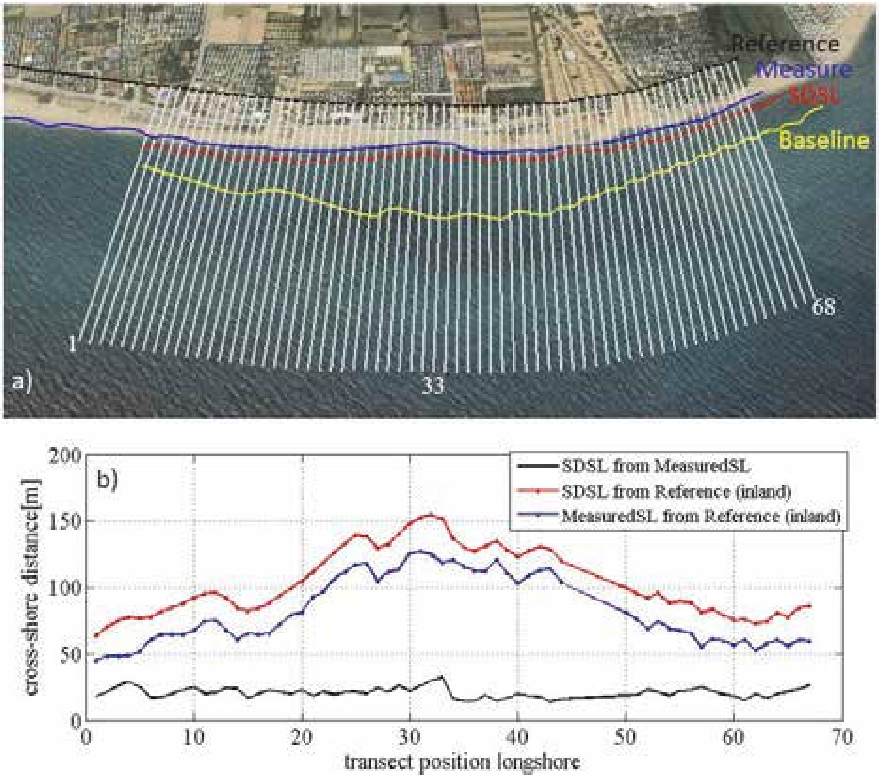

Figure 3 - a) Position of the cross-shore transects, shorelines (measured and satellite) and reference line; b) cross-shore distances between shorelines and between shorelines and the reference.

The increment in accuracy obtained through co-registration allows more reliable analysis of coastal changes in different time-scales. Here we show the applicability of this kind of product to both a long-term, (annual) and event scale. The net shoreline movement and the variation rate (calculated with a linear regression method) obtained from the long-term analysis are presented in Figure 4. Negative values indicate erosive processes. A retreat tendency is observed along the whole beach, with maximum of -6.19 m/year in the central area and minimum of -2.28 m/year in the northern zone. The most critical area shows a retreat of almost 150 m during the period of 25 years analysed (e.g. transect 33). The evolution of shoreline displacement and the yearly average of the variation rate are also represented in the Figure 4c, in terms of distance from the reference line, which is located inland (see reference line location in Figure 4a). Although some increment can be observed along the time series (e.g. years 1997, 2005 and 2015 in Figure 4c), a general retreat is clear over the 25 years, and is especially critical on transect 33. This critical zone corresponds to the area typically used by camping services (example of urban services occupying the dry beach) and which was completely removed due to long-term processes and due to extreme storm events.

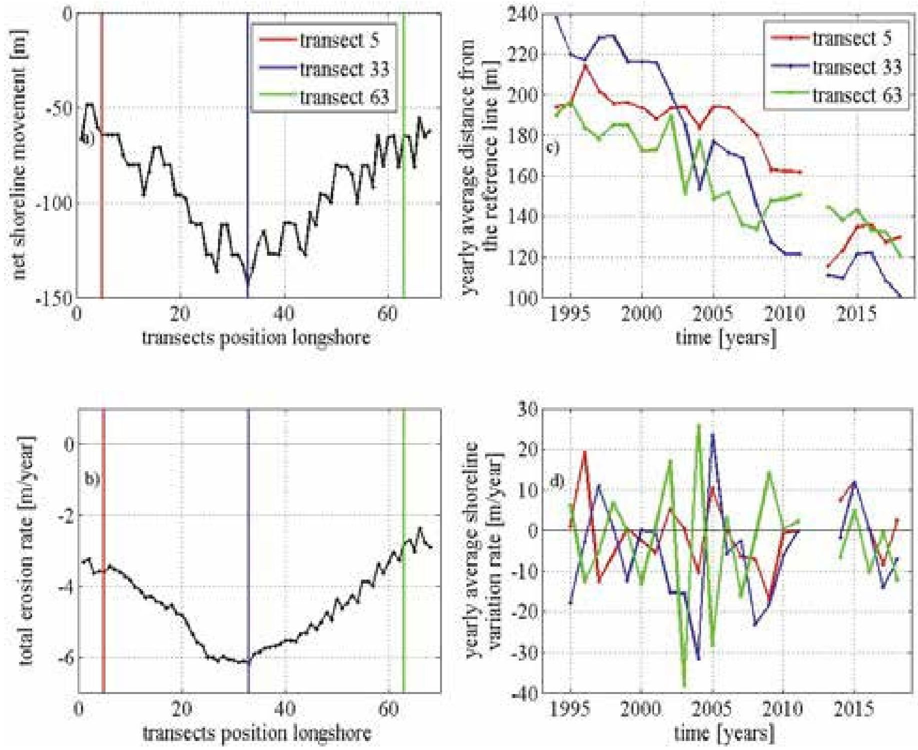

Figure 4 - Long-term analysis (SDSL 1994-2018). Spatial assessment: a) net shoreline movement along the beach, b) variation rate along the beach (negative values indicate erosive process). Temporal assessment: c) average distance from the reference line located inland, d) average shoreline variation (negative values indicate erosive process).

The most recent reported extreme events that affected Malgrat occurred over three distinct episodes, on November 2015, January 2017 and January 2020, and they contributed to the significant reduction of the beach width. The analysis of short-term shoreline variation (e.g. storms and nourishment) using satellite images is quite challenging due to the usual lack of short-term registers. In addition, clouds are frequently an issue obscuring optical detection during storms. While the problem related to clouds cannot be solved for shorelines derived from optical sensors, the increment on the frequency of acquisition and accuracy in recent satellite missions is a step forward and allows for the punctual analysis of events capable of moving considerable amounts of sand from the coast. Here, we analyze the shoreline evolution during 2015 and 2017 events individually by assessing the shorelines registered immediately before and immediately after those events.

Shoreline advance due to the nourishment carried on May 2015 is represented in Figure 5a (SL movement 1: movement from March 2015 to June 2015). A maximum advance of about 60 m was observed and agrees with the nourishment project presented by that date (see Figure 4b). The following storm event (November 2015) that hit the shoreline causing retreat was also detected (SL movement 2: movement from June 2015 to November 2015) leading to the displacement of the coast up to 40 m landward. In the following months, the retreat continued along almost the entire shoreline, moving up to 30 m landward in some areas (e.g. transects 2 to 17 and transect 57).

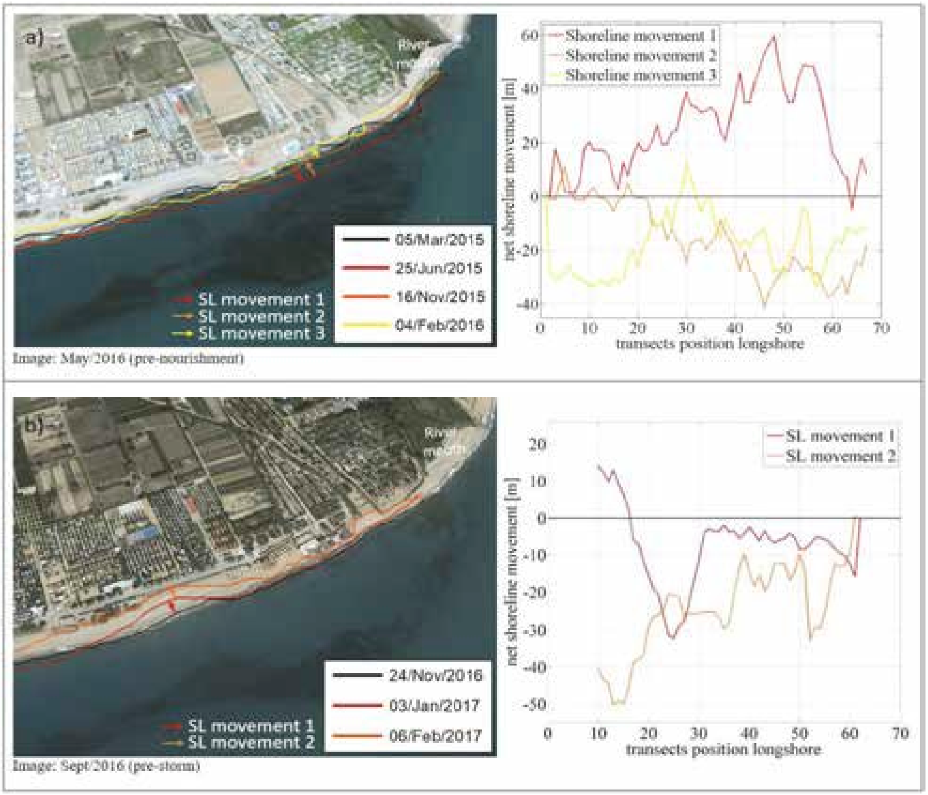

Figure 5 - Shorelines pre and post events from 2015 (nourishment and storm erosion - a) and 2017 (sequence of storm erosions - b). Left panels show the net shoreline movement between the shorelines register.

The sequence of storm events that occurred on January 2017, is represented in Figure 5b. The initial shoreline retreat observed from November 2016 to January 2017 (SL moment 1) reaches values of about 30 m in the critical area around transect 25. The erosion problem is enhanced in the following month (SL movement 2: movement from Jan/2017 to February 2017), in which the retreat occurs over the previously retreated shoreline. The shoreline advances over the camping area and reaches the sea front as observed in-situ (see Figure 2c).

Conclusions

The analysis presented here showed the potential use of large and dense SDSL time-series, populated with products from multiple satellite missions to enable the analysis of long-term variations. The importance of applying the co-registration method, which improves the spatial accuracy, on the assessment of coastal variability was also discussed. This well-known methodology has been extensively explored in the past for many purposes, but the automatic application and its use to assess coastal changes is an important innovation.

The increased frequency of acquisition in recent satellite missions allowed the analysis of short-term events to demonstrate significant shoreline variations (variations higher than the shoreline accuracy). Such advances are a step forward and improve the analysis of the effect of storm events and nourishment on shoreline variations. The possibility of using products from radar sensors (not explored here), which allow shoreline acquisition under cloudy conditions, may also grant important additional analysis of this kind of events, and will be further explored in a future work.

Acknowledgments

We acknowledge the *Ministerio para la Transición Ecológica y el Reto Demográfico* (MITERD), *Puertos del Estado* and IHCantabria for providing auxiliary data. We also thank to the *Instituto Geográfico Nacional* (IGN – Spain) and the ESA Third Party Mission agreement for making the VHR images available for this study. This work was financially supported by the Coastal Erosion Project – ESA. The Coastal Erosion project is funded via the Science for Society slice of the 5th Earth Observation Envelope Programme (EOEP-5) of the European Space Agency. Special thanks are also given to the Coastal Change Consortium, a partnership bringing together the delivery of products team, comprising ARGANS Ltd, IsardSAT & AdwaisEO, and the User Group comprising IH Cantabria, the British Geological Survey, Geological Survey of Ireland and Arctus in collaboration with the University of Quebec at Rimouski. This partnership is unique in that it brings those professional users who advise their governments together with Earth Observation technical expertise.

References

[1] Blasco, D. (2011) - *Evolución costera del Maresme Norte (Blanes-Arenys). Case*. Master's Thesis, Faculty of Civil Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain. Available online: https://upcommons.upc.edu/handle/2099.1/12961 (accessed on 21 June 2020).

[2] CEDEX – Centro de Estudios y Experimentación de Obras Públicas (2014) - *Estudios de dinámica litoral, defensa y propuestas de mejora en las playas con problemas erosivos, considerando los efectos del cambio climático: Estrategia de actuación en el Maresme*. Madrid. Available online: https://www.miteco.gob.es/es/costas/temas/proteccion-costa/Estrategia%20de%20actuacion%20en%20el%20Maresme%20(Final)%20AVANCE%20(1)-optimizado_tcm30-163212.pdf (accessed on 27 June 2020)

[3] Clerc, S (2020) - *Sentinel-2 L1C Data Quality Report.* Available online: https://sentinel.esa.int/documents/247904/685211/Sentinel-2_L1C_Data_Quality_Report (accessed on 26 June 2020)

[4] Jiménez, J.A. (2012) - *Characterising Sant Esteve's storm (2008) along the Catalan coast (NW Mediterranean)*. In Mateo, M.A., Garcia Rubies, T., (Eds) *Assessment of the Ecological Impact of the Extreme Storm of Sant Esteve's Day (26 December 2008) on the Littoral Ecosystems of the North Mediterranean Spanish Coasts*; Final Report (PIEC 200430E599); Centro de Estudios Avanzados de Blanes, Consejo Superior de Investigaciones Científicas: Blanes, Spain, 2012; pp. 31–44. Available online: http://www2.ceab.csic.es/GAME/Sant_Esteve_Storm/Contributions.html (accessed on 25 June 2020)

[5] Jiménez, J.A., Gracia, V., Valdemoro, H.I., Mendoza, E.T., Sánchez-Arcilla, A. (2011) - *Managing erosion-induced problems in NW Mediterranean urban beaches*. Ocean Coast. Man., 54, 907-918.

[6] Jiménez, J.A., Sanuy, M., Ballesteros, C., Valdemoro, H.I. (2017) - *The Tordera Delta, a hotspot to storm impacts in the coast northwards of Barcelona (NW Mediterranean).* Coast. Eng., 134, 148-158.

[7] Liu, Q., Trinder, J., Turner, I.L. (2017) - *Automatic super-resolution shoreline change monitoring using Landsat archival data: a case study at Narrabeen-Collaroy Beach, Australia.* J. Appl. Remote Sens., 11, 016036.

[8] Plana-Casado, A. (2013) - *Storm-Induced Changes in the Catalan Coast Using Lidar: The St. Esteve Storm (26/12/2008) Case*. Master's Thesis, Faculty of Civil Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain. Available online: http://hdl.handle.net/2099.1/23343 (accessed on 21 June 2020).

[9] Rovira, A., Batalla, R.J., Sala, M. (2005) - *Response of a river budget after historical gravel mining (the lower Tordera, NE Spain)*. River Res. Appl., 21, 829-847.

[10] Sanuy, M., Jiménez, J.A. (2019) - *Sensitivity of storm-induced hazards in a highly curvilinear coastline to changing storm directions. The Tordera Delta Case (NW Mediterranean).* Water, 11, 747.

[11] Scheffler, D., Hollstein, A., Diedrich, H., Segl, K., et Hostert, P. (2017) - *AROSICS: An Automated and Robust Open-Source Image Co-Registration Software for Multi-Sensor Satellite Data*, Remote Sens., 9 (7), 676.

[12] Sutherland, J., Peet, A.H., Soulsby, R.L. (2004) - *Evaluating the performance of morphological models.* Coast. Eng., 51, 917-939.

[13] Thieler, E. R., Himmelstoss, E. A., Zichichi, J. L., & Ergul, A. (2009) - *The Digital Shoreline Analysis System (DSAS) version 4.0-an ArcGIS extension for calculating shoreline change* (No. 2008-1278). US Geological Survey. doi: 10.3133/ofr20081278

[14] Vos, K., Harley, M.D., Splinter, K.D., Simmons, J.A., Turner, I.L. (2019) - *Sub-annual to multi-decadal shoreline variability from publicly available satellite imagery*. Coast. Eng., 150, 160-174.