Towards a unified sea level record: assessing the performance of global mean sea level reconstructions from satellite altimetry, tide gauges, paleo-proxies and geophysical models

Abstract

Sea-level rise is one of the most certain and costly consequences of a warming world with potentially hazardous impacts on coastal infrastructure, property, and the livelihoods of coastal communities (Nicholls and Cazenave, 2010). Since 1992, radar altimeters on board of satellites have been continuously monitoring sea-level changes with high accuracy and nearly global coverage, providing essential information on the behavior of regional and (near-) global mean sea level (GMSL) (Ablain et al., 2015). However, placing this valuable record into historical context is challenging, since estimates of GMSL before the altimetry era rely on a spatially and temporally sparse set of either tide gauge or proxy-records along the coast. In addition, these in-situ records are affected by regionally varying geoid and solid earth processes such as vertical land motion (VLM) caused by glacial isostatic adjustment (GIA) or other local processes, which may mask the global information in the records. Uncertainties in geoid and solid earth corrections in combination with different processing schemes (manifesting itself in a different weighting of the tide gauges) cause current estimates of 20th century GMSL change based on tide gauges to vary widely between ~1 and 2 mm/yr (Church and White, 2011; Jevrejeva et al., 2014; Hay et al., 2015). Furthermore, pre-industrial reconstructions of GMSL based on sea level proxies are limited to one single study (Kopp et al., 2016). The approaches and datasets used in the different published estimates of past GMSL change differ considerably, and there has been no consistent assessment of the differences between the individual reconstructions.

The objective of this proposal is to bring together a team of sea level experts to (i) objectively assess the performance of pre-altimetric sea level reconstructions using a consistent and reproducible framework of common datasets, (ii) understand and reduce the wide range of past estimates, and (iii) put the high contemporary GMSL rates obtained from satellite altimeters (~3.4 mm/yr) into a better constrained historical context.

List of confirmed members

Team members: Sönke Dangendorf (team co-leader, Germany; responsible for the communication to ISSI), Marta Marcos (team co-leader, Spain), Francisco Calafat (UK), Roland Gehrels (UK), Ben Hamlington (USA), Carling Hay (USA), Robert Kopp (USA), Roelof Rietbroek (Germany), Alvaro Santamaría-Gómez (France), Aimée Slangen (Netherlands), Phillip Thompson (USA), Guy Wöppelmann (France)

Self-supported scientists: Ole Andersen (Denmark), Eduardo Zorita (Germany)

Young scientists (to be invited after approval): Chris Piecuch (USA), Thomas Frederikse (Netherlands)

Each member confirmed his/her commitment to the proposed project.

1. Scientific rationale, goals, and timeliness of the project

Sea level is a climate variable that integrates ocean warming, melting in the cryosphere, and the terrestrial water cycle, which are all sensitive to global warming (Rietbroek et al. 2016). For this reason, sea level plays a crucial role as a climate indicator. At the same time, sea level rise impacts the world's low lying coastal zones and inhabitants by increasing the risk of coastal

flooding (especially in combination with storm surges) and concomitant effects such as salinization (Nicholls and Cazenave 2010). Hence, sea level has been defined as one of the Essential Climate Variables (ECV) by the Global Climate Observing System (GCOS). Sea level changes have been continuously monitored by high-precision radar altimeters on board of satellites since October 1992, providing a GMSL rise rate of 3.4±0.4 mm/year (1993-2014; Ablain et al, 2015). In contrast, before the altimetry era, direct estimates of GMSL changes rely on the coastal network of tide gauges that provide in situ observations of sea level relative to the land. These long-term sea level observations show that GMSL rose slower during the 20th century. Depending on how tide gauge records are combined, rates range between 1.3 and 2.0 mm/year (Church and White 2011; Jevrejeva et al. 2014; Hay et al. 2015) with uncertainties that have been estimated at about an order of magnitude smaller. The differences in rates at multi-decadal and centennial time scales between the various reconstructions are likely to arise from: (i) the selection of the tide gauge stations (e.g. Hamlington and Thompson 2015; Hay et al. 2017); (ii) the corrections (or lack of) of the VLM of the Earth's crust and of the geoid deformations induced by mass load changes that affect local tide gauge locations (Wöppelmann et al. 2014; Hay et al. 2015; Hamlington et al. 2016; Dangendorf et al. under review); (iii) the methodologies used to merge a limited number of tide gauge stations or proxy records into a GMSL series (Church and White 2011; Calafat et al. 2014; Jevrejeva et al. 2014; Hay et al. 2015; Dangendorf et al. under review); and (iv) the limited ability of all methods to separate the externally-forced long-term changes from the low-frequency fluctuations associated with internal climate variations. However, a complete understanding of the relative importance of each of those factors is lacking. This severely limits our ability to provide a unique estimate of GMSL change at century to millennial time scales and thus restrict the historical interpretation of the altimetric GMSL record.

Our goal in the proposed project is therefore to better understand the differences between existing estimates of GMSL change and to narrow, as effectively as possible, the range of estimates of GMSL rise in the past. This goal will be tackled by addressing the following specific objectives:

1. To test objectively the performance of each reconstruction approach in controlled conditions, using synthetic sea level fields, provided by state of the art climate models, where the model truth is a priori known.
2. To constrain pre-altimetry rates of GMSL in order to place the contemporary GMSL rise observed by satellite altimetry in the adequate historical context of in-situ (20th century) and proxy data (Late Holocene).

This is essential to address important questions such as whether GMSL rise is accelerating in response to global warming and whether the anthropogenic fingerprint in rising sea levels is already detectable. We expect that the results of the proposed research will lead to papers in major journals, and are consequently relevant to a broad range of climate sciences. Furthermore, due to the continued extension of the radar altimetry record, altimetry is becoming an ever more valuable tool for policymakers, and our research aims to facilitate this. The methods investigated here can also be extended far beyond the sea level application to the many other disciplines where the problem of reconstructing spatio-temporal fields using sparse observations is encountered.

To address these challenges we propose to build a multi-disciplinary international team of leading experts in sea level science with demonstrated expertise in tide gauge and satellite altimetry data analyses, numerical ocean modelling, VLM and mass load deformation, statistical methods and paleo-sea level reconstructions. To achieve our objectives we propose

to focus the project on two time periods (corresponding to two work packages plus an integration work package), as detailed in the following.

Work Package 1: 20th century GMSL reconstructions

In order to quantify and understand the differences in the resulting GMSL curves from different methodologies, we will objectively assess the performance of individual state-of-the-art GMSL reconstruction approaches (e.g. Church and White 2011; Jevrejeva et al. 2014; Ray and Douglas 2011; Hay et al. 2015; Hamlington et al. 2016; Dangendorf et al. under review) using a variety of synthetic sea level fields. We will compile a set of test fields consisting of a combination of ocean dynamics, ice-melt, GIA and hydrological fingerprints. The ocean dynamic contribution will be obtained from modelled sea surface height (SSH) fields generated by (i) historical runs from Atmosphere Ocean General Circulation Models (AOGCMs) available at the Coupled Model Intercomparison Project Phase 5 (CMIP5) data base (we plan to base our selection on earlier assessments such as those achieved by the ISSI International Team on contemporary regional and global sea level rise, http://www.issibern.ch/teams/climatemodels/) and (ii) ocean reanalysis such as SODA (Carton and Giese, 2008) or the eddy-resolving (1/12°) global model NEMO (Marzocchi et al., 2015), which should be able to resolve many of the coastal processes that are important to sea level. Fingerprints from glaciers and ice-sheet melting, hydrological changes, and GIA will be linearly added to the SSH fields. We will then create a series of surrogate datasets to simulate the near-global altimetry observations and the temporally long but spatially sparse tide gauge records. The latter will be additionally "contaminated" by synthetic time series of VLM derived using the statistics of observed GPS measurements minus GIA (i.e. a trend plus a noise term).

The surrogate datasets will be distributed among all participants who will then apply their individual reconstruction techniques. All results will be inter-compared and tested against the a priori known modelled GMSL curves. It is expected that the information provided insight on how to choose the optimal tide gauge dataset, the pros and cons of individual reconstruction approaches, and guidance on how to best integrate a priori knowledge of solid Earth and geoid corrections.

Work Package 2: Paleo GMSL (late Holocene)

Following the same approach as in WP1, a series of surrogate synthetic proxy records will also be created. Since the focus is on Late Holocene time scale, the synthetic sea level fields will be created using a millennial simulation with the Earth System model MPI-ESM-P AOGCM. The point-wise information will correspond to the locations and temporal resolution of all available proxy records from paleo sea level studies (Kopp et al. 2016) and random noise will be added to each mimicking the limitations of actual proxy records (e.g. Gomez-Navarro et al. 2016). Gaussian process regression (i.e. Kopp 2013) will be used to convert the non-equidistant proxy records and their climate model surrogates into the required temporal resolution. Paleo-sea level reconstruction techniques from Kopp et al. (2016) and Dangendorf et al. (under review) will be then applied to the surrogate time series and compared to the a priori known modelled GMSL curves.

Work Package 3: Application to observations and comparison to the altimeter record

Based on the results of WP1 and WP2 we will apply each reconstruction approach with all available and applicable a priori information to real observations. This will provide a variety of reconstructions over the late Holocene from proxies and over the 20th century from tide gauges (combined with altimetry or not). By doing this we aim to provide constrained rates of

GMSL changes over the past that will be compared to the unique near-global altimeter record since 1992. This component of the work is essential to understanding whether the elevated rate of global rise during recent decades represents an acceleration in the secular rate of change or a temporary increase due to decadal climate variability.

2. Expected outputs

The proposed research will lead to the publication of two scientific peer-review papers:

- Paper on 20th century GMSL rise using different reconstruction methods that will: (i) test the sensitivity of each method to the selection of tide gauges and the corrections applied; (ii) determine the most suitable approach(es), if any, to recover the a priori known GMSL from synthetic fields; (iii) constrain the 20th century GMSL rise rate and its uncertainties as observed by tide gauges and altimetry from the findings in (i), (ii) and (iii); and (iv) quantify the increase and the possible acceleration of GMSL rise during the altimetry period.

- Paper on sea level reconstructions during the Late Holocene that will: (i) test two approaches to reconstruct paleo sea levels and compare them to the a priori known modelled GMSL; (ii) refine the value and the uncertainties in GMSL changes during late Holocene; and (iii) quantify the probability of acceleration of GMSL rise during the last decades.

In addition to the two papers a final report will be produced, which will be used to summarize our findings and serve as a means to report back to ISSI.

3. Added value to ISSI

The expected outcome of the proposed research is highly relevant for the interpretation of the satellite altimetry GMSL observations, which represent one of the major and most crucial applications of the space missions for climate studies. By placing the current rates of GMSL rise in the appropriate historical context we will: (i) assess how the rate of present-day GMSL rise compares to earlier decades and centuries; (ii) contribute to detection and attribution studies by improving the knowledge of GMSL sensitivity to anthropogenic climate change; (iii) improve our confidence in estimates of the acceleration of GMSL rise; and (iv) potentially contribute to an improved design of future Earth observation systems. The ISSI support to build the proposed International Team will therefore aid current efforts to understand past GMSL changes as reported by satellite and by ground-based observations and will contribute to advance the state-of-the-art interpretation of long-term sea level observations.

Our proposal fits into the research field of Earth Sciences using space data fostered by ISSI. Our team is formed by scientists based in Europe and North America, thus ISSI Bern provides a location that is convenient for the majority of team members.

4. Schedule

Two four-day meetings are foreseen within this proposal, tentatively scheduled in:

- Meeting 1 in November/December 2017. Prior to the meeting the team leaders will encourage the members to contribute to the compilation and preparation of the individual datasets that will be used to build synthetic fields and surrogate records. During the meeting the complete test fields and synthetic datasets will be presented, extended if needed and provided to all team members, who will agree on the sensitivity tests to be carried out using different approaches and the timing to deliver the reconstructed GMSL curves. The common framework for the inter-comparison of reconstructions will be discussed.
- Meeting 2 in July 2018. Individual GMSL reconstructions for the 20th century and the late Holocene will be presented and inter-compared. Different skills and methods will be discussed

among all participants. The elements, structure and contributors to the two scientific papers with the main results will be agreed.

Submission of the two papers is expected before the end of 2018. The final report to ISSI will be delivered no later than spring 2019.

5. Facilities required

The facilities requested are a meeting room for 16 people with projector and internet connection. A black board/white board would also be helpful. Also, IT support for the project website is requested.

6. Financial support requested

Accommodation and per diem is requested for 12 team members (plus 2 young scientists) for the two four-day meetings. Also travel support for one of the two team co-leaders for each meeting.

References

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Jevrejeva S, Moore JC, Grinsted A, Matthews AP, Spada G (2014) Trends and acceleration in global and regional sea levels since 1807. Global and Planetary Change, 113, 11-22.

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Annexe: Short CVs of the team members and list with contact information

NAME, First Name: DANGENDORF, Sönke

Affiliation: University of Siegen, Germany

Role in the project: Co-leader (responsible for the communication to ISSI), expertise in sea level observations from tide gauges/altimetry/proxy records and their processing, sea level processes and GMSL reconstructions

Current position: Researcher (Group Leader), Department of Civil Engineering

Former Position(s): PostDoc University of Siegen (2014-2016), PhD University of Siegen (2010-2014)

Education: PhD in Civil/Coastal Engineering (University of Siegen), Diploma in Civil Engineering (University of Siegen)

Services in National and/or International Committees (last ones): Guest Editor for "*Scientific Data*" (Nature Publishing Group, since 2017), Associate Editor for "*Frontiers in Marine Science*" (since 2016), Member of the Working Group on "*Understanding sea level dynamics in the Baltic Sea region*" of Baltic Earth (since 2016), Organizing Committee of the "*Workshop on Global and Regional Sea Level Variability and Change*" at Mallorca (2015)

Honors: EGU Outstanding Student Poster (OSP) Award (2015), Outstanding PhD thesis award of the "Förderverein für Architektur und Bauingenieurwesen an der Universität Siegen" (2014); Visiting Fellowships at Hiroshima University (2016), Saitama University (2015), IMEDEA/University of the Balearic Islands (2015), University of Reading (2014), Nansen Centre (2014); Early Career Scientists Travel Grant for the E3S Future Earth Cross Community Workshop in Berlin, DAAD Travel Grants for the AGU Meetings in San Francisco (2012, 2013, 2015)

Selected Publications:

A. Arns, S. Dangendorf, J. Bender, A. Talke, C. Pattiaratchi, J. Jensen, (2017): Sea-level rise induced amplification of coastal protection design heights, *Scientific Reports*, 7, 40171

S. Dangendorf, C. Mudersbach, T. Wahl, J. Jensen (2013): Characteristics of intra-, inter-annual and decadal variability and the role of meteorological forcing: The long record of Cuxhaven, *Ocean Dynamics,* 63 (2-3):209-224

S. Dangendorf, F. M. Calafat, A. Arns, I. D. Haigh, T. Wahl, J. Jensen (2014): North Sea mean sea level variability: processes and implications, *J. Geophys. Res.*, doi:10.1002/2014JC009901

S. Dangendorf, D. Rybski, C. Mudersbach, A. Müller, E. Kaufmann, E. Zorita, J. Jensen (2014): Evidence for long-term memory in sea level, *Geophys. Res. Lett.*, 41, 15, 5530-5537.

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S. Dangendorf, M. Marcos, G. Wöppelmann, C. Conrad, R. E. M. Riva, T. Frederikse (under review): Reassessment of 20th century global mean sea level rise

I.D. Haigh, T. Wahl, E.J. Rohling, R.M. Price, C.B. Pattiaratchi, F. M. Calafat, S. Dangendorf (2014): Timescales for detecting a significant acceleration in sea level rise, *Nature Communications*, 5, 3635.

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H. Visser, S. Dangendorf, A. C. Petersen (2015): A review of trend models applied to sea level data with reference to the “acceleration-deceleration date”, *J. Geophys. Res.,* DOI: 10.1002/2015JC010716

NAME, First Name: MARCOS, Marta

Affiliation: University of the Balearic Islands, Spain

Role in the project: Co-leader, expertise in sea level observations from tide gauges and altimetry, sea level data analyses and reconstructions

Current position: Lecturer, Department of Physics

Former Position(s): Postdoctoral researcher at IMEDEA (Spanish Research Council & University of the Balearic Islands)

Education: PhD in Physics (2004) at the University of the Balearic Islands

Services in National and/or International Committees (last ones): MedCLIVAR Steering Committee (since 2012), EuroGOOS Tide Gauges Task Team (since 2015), Chief Editor in Frontiers in Marine Science, Specialty on Coastal Ocean Processes (since 2016).

Honors: : "Ramón y Cajal" Fellowship (2009); MedCLIVAR Young Scientist Award (2011)

Selected Publications:

P.L. Woodworth, J.R. Hunter, M. Marcos, P. Caldwell, M. Menéndez, I. Haigh (in press) Towards a global sea level data set. Geoscience Data Journal. doi: 10.1002/gdj3.42

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M. Marcos; M.N. Tsimplis; F.M. Calafat (2012) Inter-annual and decadal sea level variations in the North-western Pacific marginal seas. Progress in Oceanography, 105, doi: 10.1016/j.pocean.2012.04.010

NAME, First Name: ANDERSEN, Ole Baltazar

Affiliation: Danish National Space Center/DTU Space, Denmark

Role in the project: expertise in sea level observations from tide gauges and altimetry, Arctic altimetry and sea level reconstructions

Current position: Senior reserach scientist (Responsible for section "*Marine remote sensing*")

Former Position(s): Research scientist KMS geodetic division (1995-1998), Senior research scientist at KMS (1998-2004)

Education: Masters in Geophysics, University of Arhus (1992); PhD in Geophysics, University of Copenhagen (1996)

Services in National and/or International Committees (last ones): Member of the science working team for Jason-1, Jason-2, and GRACE; Member of Science Advisory Group for ESA, GPS, and GNSS mission GEROS (Launch, 2019); Chair of GMES Sentinel-3 Calibration and Validation Team, and Quality Working Team; Appointed lecturer for the Int. Assoc. Of Geodesy: Buenos Aires (2009) and St. Petersburg (2011)

Honors: Inge Lehhmans Grant to work with the University of Tasmania (1997); Danish Reserach Agency Grant to work as guest scientist at NASA, GSFC (2004)

Selected Publications:

Andersen,O. B. Cheng, Y. (2013) Long term changes of altimeter range and geophysical corrections at altimetry calibration sites, Advances in Space Research (ISSN: 0273-1177) (DOI: http://dx.doi.org/10.1016/j.asr.2012.11.027), vol: 51, issue: 8, pages: 1468-1477

Andersen, O.B. P. Knudsen and P. Berry (2010) Recent Development in High Resolution Global Altimetric Gravity Field Modeling, The Leading Edge, ISSN: 1070-485X, vol: 29, issue: 5, pages: 540-545.

Andersen O. B, Knudsen P (2009) The DNSC08 mean sea surface and mean dynamic topography. J. Geophys. Res., 114, C11, doi:10.1029/2008JC005179

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NAME, First Name: MIR CALAFAT, Francisco

Affiliation: National Oceanography Centre, Liverpool, Unites Kingdom

Role in the project: Dr. Calafat will produce one of the various sea level reconstructions using a reduced space optimal interpolation, and will assess its performance.

Current position: Senior Scientist

Former Position(s):

2014-2016 Ocean Altimetry Research Scientist, National Oceanography Centre, UK.

2013-2014 Marie Curie Postdoctoral Research Fellow, National Oceanography Centre, UK.

2011-2013 Marie Curie Postdoctoral Research Fellow, University of South Florida, USA.

2010-2011 Postdoctoral Researcher, University of the Balearic Islands, Spain.

Education: PhD in Physics (2006-2010), University of the Balearic Islands, Spain.

BSc in Physics (1997-2001), University of the Balearic Islands, Spain.

Honors: Marie Curie Postdoctoral International Outgoing Fellowship (IOF) for Career Development (3 years). University of South Florida, USA / National Oceanography Centre, UK. Award: €247,586. Funded by the European Union.

Selected Publications:

Calafat, F.M., P. Cipollini, J. Bouffard, H. Snaith, P. Féménias (2017), Evaluation of new CryoSat-2 products over the ocean, *Remote Sens. Environ.*, 191, 131-144.

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Calafat, F.M., D. Gomis, M. Marcos (2009), Comparison of Mediterranean sea level fields for the period 1961-2000 as given by a data reconstruction and a 3D model, *Global Planet. Change*, *68*, 175-184.

Calafat, F.M., D. Gomis (2009), Reconstruction of Mediterranean sea level fields for the period 1945-2000, *Global Planet. Change*, *66*, 225-234.

NAME, First Name: GEHRELS, Roland

Affiliation: University of York, United Kingdom

Role in the project: Palaeo sea-level reconstructions

Current position: Professor in Physical Geography (since 2013)

Former Position(s): Professor of Physical Geography, University of Plymouth (2007-2013), Reader in Sea-Level Studies, University of Plymouth (2004-2007), Principal Lecturer in Geography, University of Plymouth (2001-2004), Senior Lecturer in Geography (1996-2001), Lecturer in Geography, University of Plymouth (1995-1996), Postdoctoral Fellow, University of Durham (1994-1995).

Education: PhD, Geology, University of Maine (USA), 1994; MSc, Quaternary Geology, Vrije Universiteit, The Netherlands, 1989.

Services in National and/or International Committees (last ones): NERC Peer Review College (2012 – present); Marine Geology Editorial Board (2002 – present); PALSEA (PAGES/INQUA) Steering Committee (2010-present); NERC Radiocarbon Steering Committee (2010-2016); President INQUA Commission on Coastal and Marine Processes (2011-2015); UK National Correspondent UNESCO IGCP Projects 495 (2004-2009) and 588 (2010-2011); Chair North and West Europe Working Group, INQUA Commission on Coastal and Marine Processes (2007-2011); Contributing author IPCC AR5 WG1, Chapter 13, Sea-Level Change.

Honors: >60 invited and keynote lectures

Selected Publications:

Kopp, R.E., Kemp, A.C., Bittermann, K., Horton, B.P., Donnelly, J.P., Gehrels, W.R., Hay, C.C., Mitrovica, J.X., Morrow, E.D., Rahmstorf, S., 2016. Temperature-driven global sea-level variability in the Common Era, Proceedings of the Natural Academy of Sciences, doi:10.1073/pnas.1517056113.

Gehrels, W.R., Shennan, I, 2015. Sea level in space and time: revolutions and inconvenient truths. Journal of Quaternary Science 30, 131-143.

Saher, M.H., Gehrels, W.R., Barlow, N.L.M., Long, A.J., Haigh, I.D., Blaauw, M., 2015. A 600 year multiproxy record of sea-level change and the influence of the North Atlantic Oscillation. Quaternary Science Reviews 108, 23-36.

Gehrels, W.R. and Woodworth, P.L., 2013. When did modern rates of sea-level rise start? Global and Planetary Change 100, 263-277.

Gehrels, W.R., Callard, S.L., Moss, P.T., Marshall, W.A., Blaauw, M., Hunter, J., Milton, J.A., Garnett, M.H., 2012. Nineteenth and twentieth century sea-level changes in Tasmania and New Zealand. Earth and Planetary Science Letters 315-316, 94-102.

Milne, G.A., Gehrels, W.R., Hughes, C.W., Tamisiea, M.E., 2009. Identifying the causes of sea-level change. Nature Geoscience 2, 471-478, doi:10.1038/NGEO544.

NAME, First Name: HAMLINGTON, Benjamin

Affiliation: Old Dominion University

Role in the project: Sea level reconstructions using cyclostationary empirical orthogonal functions

Current position: Assistant Professor, Ocean, Earth, and Atmospheric Sciences Department, Old Dominion University, 2014-Present

Former Position(s): Research Scientist II, Cooperative Institute for Research in Environmental Sciences, Boulder, CO, 2013-2014

Education:

2007-2011: Doctor of Philosophy in Aerospace Engineering Sciences, University of Colorado at Boulder

2006-2007: Master of Science in Mechanical Engineering, Washington University in St. Louis

2002-2007: Bachelor of Science in Aerospace Engineering, Washington University in St. Louis

Services in National and/or International Committees (last ones): Member of NASA Sea Level Rise Science Team (2014-present); Member of NASA Ocean Surface Topography Science Team (2011-present)

Honors: Early Career Distinguished Research Award, 2016, Old Dominion University

Selected Publications:

Hamlington, B. D., P.R. Thompson, W. C. Hammond, G. Blewitt, and R. D. Ray, 2016: Assessing the impact of vertical land motion on twentieth century global mean sea level estimates, *J. Geophys. Res. Oceans*, **121**, 4980–4993.

Hamlington, B. D., S. H. Cheon, P. R. Thompson, M. A. Merrifield, R. S. Nerem, R. R. Leben, and K.-Y. Kim, 2016: An ongoing shift in Pacific Ocean sea level, *J. Geophys. Res. Oceans*, **121**, 5084–5097.

Hamlington, B. D., Leben, R.R., Kim, K.-Y., Nerem, R.S., Atkinson, L.P., Thompson, P.R. 2015: The effect of the El Niño-Southern Oscillation on U.S. regional and coastal sea level, *J. Geophys. Res. Oceans*, **120**, 3970–3986.

Hamlington, B. D., and P. R. Thompson, 2015: Considerations for estimating the 20th century trend in global mean sea level. *Geophys. Res. Lett.*, **42**, 4102–4109.

Hamlington, B.D., Strassburg, M.W., Leben, R.R., Han, W., Nerem, R.S., Kim, K.-Y., 2014: Uncovering an anthropogenic sea-level rise signal in the Pacific Ocean, *Nat. Clim. Change,* **4***,* 782-785.

NAME, First Name: HAY, Carling

Affiliation: Department of Earth and Planetry Sciences, Havard University, USA

Role in the project: Benchmark the multi-model Kalman smoother methodology of Hay et al. (2015) with synthetic sea-level observations to better understand the spread in historical global mean sea level estimates.
Current position: Postdoctoral Fellow Department of Earth and Planetry Sciences at Havard University (since 2012)

Former Position(s): Postdoctoral Fellow Department of Earth and Planetry Sciences at Rutgers University (2014-2017)

Education:

University of Toronto, Toronto, Canada: Ph.D., Physics, 2012, Thesis Title: *The Interaction of Ice Sheets with the Ocean and Atmosphere*, Advisors: Prof. G.W.K. Moore and Prof. Jerry X. Mitrovica

McGill University, Montréal, Canada: Bachelor of Science, with Great Distinction, 2006, Physics Major

Selected Publications:

Hay, C., Morrow, E., Kopp, R. E., and J. X. Mitrovica (2016). On the robustness of Bayesian fingerprinting estimates of global sea-level change, in press, *Journal of Climate.*

Hay, C., Lau, H., Gomez, N., Austermann, J., Powell, E., Mitrovica, J. X., Latychev, K., and D. Wiens (2016). Sea-level fingerprints in a region of complex Earth structure: The case of WAIS, *Journal of Climate*, **30**, 1881-1892.

Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Gehrels, W. R., **Hay, C**., Mitrovica, J. X., Morrow, E., and S. Rahmstorf (2015) Temperature-driven global sea-level variability in the Common Era, *PNAS*, **113**, E1434-E1441.

Kopp, R. E, **Hay, C**., Little, C. M, and J. X. Mitrovica (2015). Geographic variability of sea-level change, *Current Climate Change Reports,* **1**, 192-204.

Hay, C., Morrow, E., Kopp, R.E., and J.X. Mitrovica (2015). Probabilistic reanalysis f 20th century sea-level rise. *Nature*, **517**, 481-484.

Mitrovica, J. X., **Hay, C.**, Morrow, E., Kopp, R. E., Dumberry, M., and S. Stanley (2015). Reconciling past changes in Earth rotation with 20th century global sea-level rise: resolving Munk's enigma, *Science Advances*, **1**, e1500679.

Hay, C., Mitrovica, J. X., Gomez, N., Creveling, J. R., Austermann, J., and R. E. Kopp (2014). The sea-level fingerprints of ice-sheet collapse during interglacial periods. *Quaternary Science Reviews,* **87**, 60-69.

Hay, C., Morrow, E., Kopp, R. E., and J. X. Mitrovica (2013). Estimating the sources of global sea level rise with data assimilation techniques. *Proceedings of the National Academy of Science*, **110**, 3692-3699.

Mitrovica, J. X., Gomez, N., Morrow, E., **Hay, C**., Latychev, K., and M.E. Tamisiea (2011). On the robustness of predictions of sea-level fingerprints, *Geophysical Journal International*, **187**, 729-742.

NAME; First Name: KOPP, Robert

Affiliation: Rutgers University, New Jersey, USA

Role in the project: sea level reconstructions using Gaussian Process Regression, paleo sea level reconstructions

Current position: Rutgers University, Professor, Dept. of Earth and Planetary Sciences (2017-present) and Associate Director, Rutgers Energy Institute (2011-present)

Former Positions: Rutgers University, Associate Professor (2014-2017) and Assistant Professor (2011-2014), Dept. of Earth and Planetary Sciences; U.S. Department of Energy, AAAS Science & Technology Policy Fellow (2009-2011); Princeton University, Science, Technology & Environmental Policy Postdoctoral Research Fellow (2007-2009)

Education: University of Chicago, S.B., Geophysical Sciences, 2002; California Institute of Technology, M.S., Geobiology, 2005; California Institute of Technology, Ph.D., Geobiology, 2007

Services in National and/or International Committees (last ones): Lead Author, U.S. Global Change Research Program Climate Science Special Report (2016-2018); Committee Member, National Academies Project on Assessing Approaches to Updating the Social Cost of Carbon (2015-2017); Intergovernmental Panel on Climate Change, Contributing Author for Fifth Assessment Report (AR5) Working Groups 1 and 2 (2011-2014)

Honors: Rutgers–New Brunswick Chancellor's Scholar (2015-); Leopold Leadership Fellow (2015–2016); International Union for Quaternary Research (INQUA) Sir Nicholas Shackleton Medal (2015); American Geophysical Union (AGU) William Gilbert Medal (2012); Kavli Fellow (2012); Award for Special Service, U.S. Department of Energy (2010)

Selected Publications:

R. E. Kopp, A. C. Kemp, K. Bittermann, J. P. Donnelly, W. R. Gehrels, C. C. Hay, J. X. Mitrovica, E. D. Morrow, S. Rahmstorf, and B. P. Horton (2016). Temperature-driven global sea-level variability in the Common Era. *Proceedings of the National Academy of Sciences* 113, E1434-E1441.

C. C. Hay, E. D. Morrow, R. E. Kopp, and J. X. Mitrovica (2015). Probabilistic reanalysis of 20th century sea-level rise. *Nature* 517, 481–484.

R. E. Kopp, R. M. Horton, C. M. Little, J. X. Mitrovica, M. Oppenheimer, D. J. Rasmussen, B. H. Strauss, and C. Tebaldi (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide gauge sites. *Earth's Future* 2: 287–306.

R. E. Kopp, F. J. Simons, J. X. Mitrovica, A. C. Maloof and M. Oppenheimer (2013). A probabilistic assessment of sea level variations within the Last Interglacial stage. *Geophys. J. Int.* 193, 711-716.

R. E. Kopp, F. J. Simons, J. X. Mitrovica, A. C. Maloof, and M. Oppenheimer (2009). Probabilistic assessment of sea level during the last interglacial stage. *Nature* 462: 863-867.

NAME, first name: RIETBROEK, Roelof

Affiliation : University of Bonn, Institute of Geodesy and Geoinformation

Role in the project: Computation of sea level fingerprints of surface mass loading, and provision of altimetry data.

Current position: Postdoc, University of Bonn

Former Position(s):

2009 - 2014	Researcher at Bonn University (Astronomical, Physical and Mathematical Geodesy)
2007 - 2009	Researcher at Section 1.3 Gravity Field and Gravimetry at Helmholtz Centre Deutsches GeoForschungsZentrum (GFZ)

Education:

2014 Phd in Geodesy (Dr.-Ing) Bonn University

2000 -2007 Msc Aerospace Engineering, Delft University of Technology, Netherlands

Services in National and/or International Committees (last ones):

2017-2018 Union early career representative of the European Geosciences Union

2014- Early career representative of the geodesy division of the European Geosciences Union

Honors: 2014, EGU Division Outstanding Young Scientists Award

Selected Publications

Rietbroek, Roelof, S.-E. Brunnabend, J. Kusche, J. Schröter, and C. Dahle. “Revisiting the Contemporary Sea Level Budget on Global and Regional Scales.” *Proceedings of the National Academy of Sciences*, 2016, 201519132. doi:10.1073/pnas.1519132113.

Schall, Judith, A. Löcher, J. Kusche, R. Rietbroek, and A. Sudau. “Consistency of Geoid Models, Radar Altimetry, and Hydrodynamic Modelling in the North Sea.” *Marine Geodesy*, 2016. doi:10.1080/01490419.2016.1152334.

Kusche, J, B Uebbing, R Rietbroek, CK Shum, and ZH Khan. “Sea Level Budget in the Bay of Bengal (2002–2014) from GRACE and Altimetry.” *Journal of Geophysical Research: Oceans*, 2016. doi:10.1002/2015JC011471.

R. Rietbroek, S. E. Brunnabend, C. Dahle, J. Kusche, F. Flechtner, J. Schröter, and R. Timmermann. Changes in total ocean mass derived from grace, gps, and ocean modeling with weekly resolution. Journal Of Geophysical Research-Oceans, 114(C11004):C11004, 2009

R. Rietbroek, S. E. Brunnabend, J. Kusche, and J. Schröter. Resolving sea level contributions by identifying fingerprints in time-variable gravity and altimetry. Journal of Geodynamics, 59:72–81, 2012.

Schrama, E. J.; Wouters, B. & Rietbroek, R. A mascon approach to assess ice sheet and glacier mass balances and their uncertainties from GRACE data. Journal of Geophysical Research: Solid Earth, 2014, 119, 6048–6066

Jensen, L.; Rietbroek, R. & Kusche, J. Land water contribution to sea level from GRACE and Jason measurements Journal of Geophysical Research: Oceans, Wiley Online Library, 2013

NAME, first name: SANTAMARIA-GOMEZ, Alavro

Affiliation: University of Toulouse, UPS, France

Role in the project: Vertical land movements from space techniques, data analysis

Current position: Physicien Adjoint (Associate Professor)

Former Position(s): Marie-Curie Research Fellow (2014-2016), University of La Rochelle, France and University of Tasmania, Australia; Research Engineer, National Geographic Institute, Spain (2010-2013); Geodetic Engineer, National Geographic Institute, Spain (2006); Land suveyor, Spain (2002, 2005);

Education: PhD in Geodesy (*Doctoral School of Astronomy and Astrophysics, Ile-de-France, France Laboratory of Research in Geodesy (LAREG), IGN, France,* **Dissertation:** *Estimation of crustal vertical movements with GPS in a geocentric frame, within the framework of the TIGA project*); Geodesy and Cartography Engineer (Masters), Technical University of Madrid, Spain (2002-2004); Land Surveying Technical Engineer (Bachelors), University of Salamanca, Spain (1997-2001)

Services in National and/or International Committees (last ones): Chairman of IAG Joint Working Group 3.2 on Constraining vertical land motion of tide gauges (since 2015); Second IGS reprocessing campaign (2013-2015); Scientific Responsible of the University of La Rochelle GPS Analysis Centre

Honors: Young Author Award, International Association of Geodesy (Article: Long-term vertical land motion from double-differenced tide gauge and satellite altimetry data*. Alvaro Santamaría-Gómez, Médéric Gravelle, Guy Wöppelmann. Journal of Geodesy, 88(3), 207-222, 2014*)

Selected Publications:

Wöppelmann, G., Letetrel, C., **Santamaria, A**., Bouin, M.-N., Collilieux, X., Altamimi, Z., Williams, S.D.P., Martin Miguez, B. *Rates of sea-level change over the past century in a geocentric reference frame*. (2009) Geophysical Research Letters, 36 (12). **Cited 99 times** (Scopus).

Santamaría-Gómez, A., Bouin, M.-N., Collilieux, X., Wöppelmann, G. *Correlated errors in GPS position time series: Implications for velocity estimates*. (2011) Journal of Geophysical Research: Solid Earth, 116 (1), B01405. **Cited 66 times** (Scopus).

Santamaría-Gómez, A., Gravelle, M., Collilieux, X., Guichard, M., Míguez, B.M., Tiphaneau, P., Wöppelmann, G. *Mitigating the effects of vertical land motion in tide gauge records using a state-of-the-art GPS velocity field.* (2012) Global and Planetary Change, 98-99, pp. 6-17. **Cited 54 times** (Scopus).

Nahmani, S., Bock, O., Bouin, M.-N., **Santamaría-Gómez, A**., Boy, J.-P., Collilieux, X., Métivier, L., Panet, I., Genthon, P., De Linage, C., Wöppelmann, G. *Hydrological deformation induced by the West African Monsoon: Comparison of GPS, GRACE and loading models.* (2012) Journal of Geophysical Research: Solid Earth, 117 (5), B05409. **Cited 20 times** (Scopus).

Wöppelmann, G., Le Cozannet, G., De Michele, M., Raucoules, D., Cazenave, A., Garcin, M., Hanson, S., Marcos, M., **Santamaría-Gómez, A**. *Is land subsidence increasing the exposure to sea level rise in Alexandria, Egypt?* (2013) Geophysical Research Letters, 40 (12), pp. 2953-2957. **Cited 14 times** (Scopus).

NAME, First Name: SLANGEN, Aimée

Affiliation: Royal Netherlands Institute for Sea Research (NIOZ), Department of Estuarine & Delta Systems (EDS), PO Box 140, 4400 AC Yerseke, The Netherlands

Role in the project: Sea-level modelling, climate model analysis

Current position: Tenure Track Scientist at NIOZ

Former Position(s): Postdoc at IMAU (Utrecht, Netherlands, 2016-2017), Postdoc at CSIRO (Hobart, Australia, 2013-2016)

Education: PhD at IMAU (Utrecht, Netherlands, awarded Dec. 2012), BSc & MSc Meteorology (Wageningen University, Netherlands)

Services in National and/or International Committees (last ones): ISSI team on Contemporary regional and global sea level rise (Benoit Meyssignac); WCRP-CliC targeted activity on Glacier Modelling Intercomparison GlacierMIP (Ben Marzeion & Regine Hock).

Honors: SIEF John Stocker Postdoctoral Fellowship (276k AUD, 4% success rate)

Selected Publications:

Slangen, A.B.A., F. Adloff, S. Jevrejeva, P.W. Leclercq, B. Marzeion, Y. Wada and R. Winkelmann (2017) A review of recent updates of sea level projections at global and regional scales, Surveys in Geohysics, 38(1), 385-406, doi: 10.1007/s10712-016-9374-2.

Slangen, A.B.A., J. A. Church, C. Agosta, X. Fettweis, B. Marzeion and K. Richter (2016) Anthropogenic forcing dominates global mean sea-level rise since 1970, Nature Climate Change, 6, 701-705, doi: 10.1038/NCLIMATE2991.

Slangen, A. B. A., and J. A. Church, X. Zhang and D. Monselesan (2015) The sea-level response to external forcings in historical simulations of CMIP5 climate models, Journal of Climate, 28(21), 8521-8539, doi: 10.1175/JCLI-D-15-0376.1.

Slangen, A. B. A., and M. Carson, C.A. Katsman, R.S.W. van de Wal, A. Koehl, L.L.A. Vermeersen and D. Stammer (2014) Projecting twenty-first century regional sea-level changes, Climatic Change, 124, 317-332, doi: 10.1007/s10584-014-1080-9.

Slangen, A.B.A., C.A. Katsman, R.S.W. van de Wal, L.L.A. Vermeersen and R.E.M. Riva (2012) Towards regional projections of twenty-first century sea-level change based on IPCC SRES scenarios, Climate Dynamics, 38(5-6), 1191-1209, doi: 10.1007/s00382-011-1057-6.

NAME, First Name: THOMPSON, Philip R.

Affiliation: University of Hawaii

Role in the project: Sea level reconstructions using area-weighting approaches, sea level processes, tide gauges

Current position: Associate Director of the University of Hawai'i Sea Level Center (since 2014)

Former Position(s): Assisstant Researcher of the University of Hawai'i Sea Level Center (2012-2014)

Education: PhD in Physica Oceanography, University of South Florida, Tampa, FL, USA (2012); B.S. Physics, North Carolina State University, Raleigh, NC, USA (2004)

Services in National and/or International Committees (last ones): Supervises the maintenance, expansion, and dissemination of the tide gauge sea level datasets and products provided to the research community by the UHSLC; Tide gauge global mean sea level index for the Climate.gov Climate Dashboard (https://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level); Lead author of the sea level section in the 2016 BAMS State of the Climate Report. Co-author for 2012-2015; Session Chair for sea-level-related sessions at 2013-2015 AGU meetings

Selected Publications:

Thompson, P. R., M. A. Merrifield, J. R. Wells, and C. M. Chang (2014), Wind-driven coastal sea level variability in the Northeast Pacific, Journal of Climate, doi:10.1175/JCLI-D-13-00225.1.

Thompson, P. R., G. T. Mitchum (2014). Coherent sea level variability on the North Atlantic western boundary, Journal of Geophysical Research – Oceans, doi:10.1002/2014JC009999.

Thompson, P. R., and M. A. Merrifield (2014). A unique asymmetry in the pattern of recent sea level change, Geophysical Research Letters, doi:10.1002/2014GL061263.

Hamlington, B. D., R. R. Leben, K.-Y. Kim, R. S. Nerem, L. P. Atkinson, P. R. Thompson (2015). The Effect of the El Niño-Southern Oscillation on Coastal and Regional Sea Level in the United States, Journal of Geophysical Research – Oceans, doi:10.1002/2014JC010602.

Hamlington, B. D., P. R. Thompson (2015). Considerations for Estimating the 20th Century Trend in Global Mean Sea Level, Geophysical Research Letters, doi:10.1002/2015GL064177.

Hamlington, B. D., S. H. Cheon, P. R. Thompson, M. A. Merrifield, R. S. Nerem, R. R. Leben, and K.-Y. Kim (2016), An ongoing shift in Pacific Ocean sea level, Journal of Geophysical Research – Oceans, doi:10.1002/2016JC011815.

Hamlington, B. D., P. R. Thompson, W. C. Hammond, G. Blewitt, and R. D. Ray (2016), Assessing the impact of vertical land motion on 20th century global mean sea level estimates, Journal of Geophysical Research – Oceans, doi:10.1002/2016JC011747.

Thompson, P. R., C. G. Piecuch, M. A. Merrifield, J. P. McCreary, E. Firing (2016). Forcing of recent decadal variability in the Equatorial and North Indian Ocean, Journal of Geophysical Research – Oceans, doi:10.1002/2016JC012132.

Thompson, P. R., B. D. Hamlington, F. W. Landerer (2016). Are long tide gauge records in the wrong place to measure global sea level rise?, Geophysical Research Letters, doi:10.1002/2016GL070552.

NAME, First Name: WÖPPELMANN, Guy

Affiliation: University of La Rochelle, France

Role in the project: Vertical land movements from space techniques, long records from tide gauges, data analysis

Current position: Full Professor (permanent position)

Former Position(s): Associate Professor (2007-2012)

Education: PhD in space geodesy from the "Observatoire de Paris", France.

Services in National and/or International Committees (last ones): Chair of the science steering group of the Global sea level observing program (GLOSS) under the Intergovernmental Oceanographic Commission of UNESCO (since 2012).

Selected Publications:

Wöppelmann G. & M. Marcos (2016). Vertical land motion as a key to understanding sea level change and variability. Reviews of Geophysics, 54, 64-92.

Wöppelmann G., M. Marcos, A. Santamaria-Gomez, *et al*. (2014). Evidence for a differential sea level rise between hemispheres over the twentieth century. Geophysical Research Letters, 41, 1639-1643.

Wöppelmann G., M. Marcos, A. Coulomb, *et al*. (2014). Rescue of the historical sea level record of Marseille (France) from 1885 to 1988, and its extension back to 1849-1851. Journal of Geodesy, 88, 869-885.

Wöppelmann G., Le Cozannet, M. De Michele, et al. (2013). Is land subsidence increasing the exposure to sea level rise in Alexandria, Egypt? Geophysical Research Letters, 40, 2953-2957.

Further details in http://lienss.univ-larochelle.fr/Guy-Woppelmann-1337

NAME, First Name: ZORITA, Eduardo

Affiliation: Institute of Coastal Research, Helmholtz-Zentrum Geesthacht (HZG)

Role in the project: Provide simulated sea-level data from millennial paleo-climate simulations.; design

Present position: Senior Scientist at HZG

Former Position(s): Post-doc scientist at University Pierre et Marie Curie (Paris, 1994-1995); post-doc scientist at Max-Planck-Institute for Meteorology (Hamburg, 1989-1993)

Education: Degree in Physics(University Zaragoza, Spain, 1984), doctorate in Solid State Physics (U. Zaragoza, 1988)

Services in National and/or International Committees (last ones): Past Global Changes 2K Euro-Mediterranean Working group

Honors: Bert-Bolin Fellow University of Stockholm

Selected Publications:

Hünicke B and Zorita E. Statistical analysis of the acceleration of Baltic mean sea-level rise, 1900-2012. Frontiers Marine Sciences, doi:10.3389/fmars.2016.00125 (2016)

Gagen M., Zorita E., McCarroll D., Zahn M., Young G., Robertson I. North Atlantic summer storm tracks over Europe dominated by internal variability over the past millennium. Nature Geosciences 9, 630-637. doi:10.1038/ngeo2752 (2016)

Ljungqvist F.C., Krusic P.J., Sundqvist H.S., Zorita E.,Brattström G. and Frank D. Northern Hemisphere hydroclimate variability over the past twelve centuries. Nature 532, 94–98 doi:10.1038/nature17418 (2016)

Ocaña V., Zorita E., and Heimbach P. Stochastic secular trends in sea level rise. J. of Geophys. Res., 121, 2183–2202 DOI: 10.1002/2015JC011301 (2016)

Dangendorf S., Marcos M., Müller A., Zorita E., Riva R., Berk. K., Jensen J. Detecting anthropogenic footprints in sea level rise. Nature Communications 6, doi:10.1038/ncomms8849 (2015)

Dangendorf S, Rybski D, Murdersbach C, Müller A. Kaufmann, Zorita E, Jensen J. Evidence for long-term memory in sea level. Geophys. Res. Lett. 41, 5530-5537, doi:10.1002/2014GL060538 (2014)

von Storch, H. von, E. Zorita, J. M. Jones, Y. Dmitriev. F. González and S. F. B. Tett. Reconstructing past climate from noisy data. Science 306, 679-682 (2004)

List of Participants ISSI International Team Proposal:

Name	Institution	email	Address	Telephone	Fax
Sönke Dangendorf	University of Siegen	soenke.dangendorf@uni-siegen.de	Paul-Bonatz-Str. 9-11, 57076 Siegen, Germany	+49 271 740 2518	+49 271 740 2722
Marta Marcos	IMEDEA	marta.marcos@uib.es	Miquel Marques 21, 07190 Esporles, Spain	+34 971611337	+34 971611761
Roland Gehrels	University of York	roland.gehrels@york.ac.uk	Wenworth Way, Heslington, York, UK, Y010 5NG	+44 1904 324376	+44 1904 322998
Robert Kopp	Rutgers University	Robert.Kopp@rutgers.edu	Civic Square Building, Rm. 248, Bloustein School of Planning & Public Policy, 33 Livingston Ave., New Brunswick, NJ, USA	+1 7322002705	-
Eduardo Zorita	HZG	eduardo.zorita@hzg.de	Max-Planck-Straße 1, 21502 Geesthacht, Germany	+49 4152 87-1856	+49 4152 87-1888
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Ole Anderson	DTU	oa@space.dtu.dk	Elektrovej bldg 327, DK-2800 Lyngby, Denmark	+45 41562653	-
Aimee Slangen	NIOZ	aimee.slangen@gmail.com	Landsdiep 4, 1797 SZ 't Horntje (Texel), Netherlands	+31 113 577 300	-
Phil Thompson	University of Hawaii, UHSLC	philiprt@hawaii.edu	1000 Pope Road, MSB 317, Honolulu, HI 96822	+1 808 956-6574	-
Ben Hamlington	Old Dominion University	bhamling@odu.edu	406 OCEANOGRAPHY&PHYSICS BLDG, Norfolk, VA 23529, USA	+1 757-683-5972	-
Carling Hay	Havard & Rutgers University	carlinghay@fas.harvard.edu	20 Oxford St., Cambridge, MA, 02144, USA	+1 617 496 3835	-
Guy Wöppelmann	University of La Rochelle	guy.woppelmann@univ-lr.fr	Bâtiment ILE - Laboratoire LIENSs, 2 rue Olympe de Gouges, F-17000 La Rochelle, France	+33-5-46-45-86-13	-
Alvaro Santamaria Gomez	University of La Rochelle	alvaro.santamaria@univ-lr.fr	14 avenue Edouard Belin, F-31400 Toulouse, France	+33 5 61 33 46 16	-
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