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Interactive comment on "How to explain variations in sea cliff erosion rates? Insights from a literature synthesis" *by* Mélody Prémaillonet al.

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We wish to thank Cherith Moses (reviewer 2) for reviewing this manuscript and help us improve it.

Overview comments: The paper seeks to explain variations in sea cliff erosion rates, using a global database populated by cliff erosion rate data derived from scientific literature and national databases up to 2016. Marine and climate forcing factors are derived from models and data reanalysis in order to provide a uniformity of approach. Sea cliff lithological factors are characterised using the Hoek and Brown (1997) classification system, again in order to provide a uniform approach, and cliff height is been extracted from the 8" global DEM. The paper

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Discussion paper

represents the most comprehensive collation and analyses of rock coast erosion data to date and is scientifically important in two key respects. First, it provides analyses and insights into key factors controlling rock coast erosion rates on a global scale. Second, it illustrates limitations of existing studies/current gaps in knowledge in assessing the relative importance of lithological, subaerial and marine forcing factors. In so doing, it helps to set a new research agenda for the study of rock coast erosion dynamics and this could usefully be made clearer in the paper.

To best illustrate limitations of existing studies we added a last paragraph in the discussion: 4.2.5. Toward a new rocky coast cliff research agenda This bibliographic synthesis has highlighted the strengths and weaknesses of the current rocky coast research efforts. The last three decades's trend has gone towards increasing the quality and the resolution of cliff recession data and on documenting growing number of sites; which is good. What this study highlights however is a lack of description of critically useful parameters to understand cliff evolution dynamics: (i) cliff height; (ii) finer rock mass characteristics description, in particular weakening phenomena such as weathering and fracturing; and (iii) foreshore description, in particular its type (sand beach/pebble beach/rock platform) and geometry (elevation, slope, width). Moreover, the geographical distribution of studied sites highlight a major gap of knowledge under extreme climates (tropical, equatorial and glacial) or for slowly retreating cliffs. We also found that literature concerned with cliff retreat was not simultaneously trying to link shore platform processes to cliff retreat or how local variations affected cliff retreat specifically.

The conclusion is that rock resistance, rather than rock type per see, is a key influencing factor and that the number of frost days influence the erosion rates of only weak rock sea cliffs. Rainfall amount and marine forcing factors show no significant relationships with cliff erosion rates. This is interesting in that there is a keen debate on the importance of subaerial (weathering) versus marine forc-

ing factors in the development of rock shore platforms, which are an integral component of the rock coast system. This debate extends also to cliffs. For example, it is known on the Chalk of SE England that most rockfalls occur during the winter (May, 1971; Hutchinson, 1972) associated with increased rainfall and lower temperatures. Lawrence et al. (2013) assess the contribution of sea water weakening to chalk cliff instability and Lageat et al. (2006) and Henaff et al. (2002) assess the influence of elevated groundwater and rock saturation associated with long periods of antecedent rainfall. Although this study assesses cliff erosion rates in relation to temperature variation, frost frequency and amount of rainfall, it would be interesting to give some consideration to duration of rainfall (as a proxy for degree of rock saturation) to see if this is important.

We agree that rock saturation may be an important phenomenon. Following your remark, we investigated how it could be characterized effectively. Rock saturation is a combination of two parameters: rock reservoir capacity and efficiency of rainfalls to load the aquifer. We explored several ways to characterise those two parameters but could not work them out in publishable state within the imparted correction deadline. An element worth noting is that our approach aims at grasping the general trends rather than explaining specific collapse events. Nevertheless, your remark is very valuable and is one of the strands towards which GlobR2C2 will be extended in the future. You will find in the following lines the state we reached in this endeavour.

- For rainfall: the main issue was to find a rainfall data set suitable for such an analysis. The putative dataset needs to propose a chronicle of rainfall with a fine enough temporal (e.g. daily or hourly) and spatial (tens of kilometres at the worst) sampling step at global scale starting from the mid-20th century. The closest we found, and well short of these requirements, was NASA's TRMM (Tropical Rainfall Measuring Mission) rainfalls data set, which spans 17 years of record (1997-2015) for grid cells of 0.25° x 0.25° at 7 hours time step between 50°N and 50°S. We would be delighted to hear about other data sources. And once the data set is flagged, there'd still be a need to flag the appropriate information parameter to describe the rainfall regimes in a discriminant way to characterise aquifer-loading efficiency from rainfall. This is currently beyond our field of expertise. Exploratory tests with the global Koeppen-Geiger climate zone classification was not fine enough to discriminate cliff retreat sites.

- For rock capacity characterisation. We identified the GLHYMPS global database of Gleeson et al., 2014. This database maps at global scale values of porosity and permeability. We need further investigation and bibliographic work to find a way to integrate those values in the database. We seek to identify a well-established macroscopic parameter similar to the Hoek and Brown rock mass rating index with classes that would characterise if the rock would behave as a reservoir or not. Again, this goes beyond the initial scope of our paper.

More specific comments: Page 1 Line 3: 'It turns into variable erosion rates' suggest amending this to 'Cliff erosion rates are highly variable over 4 orders' in order to improve clarity.

The amendment was done.

Are these figures from the database? If so, it may be better to give the variation in rates after describing the database.

These figures were already known from Sunamura's work in 1992. We appended this information in the abstract.

Line 6: it would be helpful to be clear about what is meant by erosion rate, rate of cliff-top retreat, volume of material removed? Is GlobR2C2 populated entirely with erosion rate data from publications? How is the Cerema national database incorporated? There is mention in the paper of the Eurosion database – is this also incorporated into GlobR2C2? The Eurosion database is being updated and extended by the Emodnet Geology project and so there are new data, that the au-

thors may wish to investigate, available at http://www.emodnet-geology.eu/data-products/ (coastal behaviour). I am wondering if the title is an accurate reflection of the database if it incorporates more than the scientific published literature.

Several items are contained in this remark. Let us review them on by one:

Erosion rate. In the abstract, the mention of this term was completed like this "...erosion rates from publications, ..." to clarify as required. In the main text, we use cliff retreat rate when appropriate. The database aggregates cliff evolution quantities from a variety of methods and practices. The database records both, the original quantitative information, with a name labelling the method used. We then grouped the various methods in 1D, 2D, 3D higher-order measurement categories. Section 2.3.4 Measure description is dedicated to document this process. We think that the generality of "cliff retreat rate" is sufficiently encompassing to be used in the abstract without entering in any technicality.

CEREMA database. The Cerema national database incorporation is described into a dedicated section (2.3.5). For more clarity we added its specific contribution to the data set. "The French CEREMA institute published a systematic national coastal cliff recession inventory Perherin et al., 2012) based on aerial photograph comparison every 200 meters stretch of cliff along the entire French metropolitan coastline (1800 km of coastal rocky cliffs, it correspond to 465 (53%) values in the database).)"

Emodnet and Eurosion. We did not use the "data products" because the original data is hidden behind a complex processing. On the contrary, we use available local case studies from Eurosion when the completeness of the data is enough for our purpose .

Line 12: space between numerical value and SI symbol (throughout).

Spaces between numerical value and SI symbols have been checked all along the document

Line 13: Sentence beginning 'every other relations.' Could be recast to improve

clarity.

It has been rephrased

Line 18: fundamental driver suggest adding ‘of cliff retreat’.

The amendment was done.

Line 19: Remove “ after limited.

It is a mistake, we forgot the opening “, we put it before "our understanding

It would be helpful, in the introduction, to provide more context on the role of rock shore platforms in the dynamics of coastal rock cliff erosion dynamics. Although shore platforms are mentioned it would be helpful, for readers not familiar with the rock coast system, to set the context by outlining all of the key components. For example, Fig. 2 could usefully show the shore platform.

We think the shore platform is already present in our description of the processes leading to cliff erosion. To make it clearer to both reviewer we improved the figure 2 and added some sentences within the introduction to better articulate between the shore platform and rock coast erosion.

Page 2

Line 12: Sentence beginning ‘Climate through remove the s from precipitations; prepare for it?

The amendment was done.

Fig. 2 is referred to on line 16 and Fig. 5 on line 29 – Figs. 3 and 4 are not mentioned refer to Figs in order throughout.

We modified figures numbering to follow the sequential order.

Par beginning line 19: ‘they are inconclusive because it would be helpful to have more context on the focus of these papers as they did not necessarily set out to

analyse the contribution of each factor etc., perhaps due to data limitations?

We add more context and consequently this part changes to: “Those studies are often risk management (Gibb, 1978; Hapke et al., 2009). Or they can be focused on a certain type of rock to understand cliff dynamics (Moses and Robinson, 2011) (moses). This implies that those studies cannot be use to describe global retreat drivers because : (i) they do not analyse the contribution of each driver. (ii) they remain too local and characterise a narrow range of forcings (e.g. climate, homogeneous lithology . . .) ”

Par beginning line 29: it would be helpful to have some more detail on the type of study – what they measure, degree of accuracy, limitations etc. (historical maps, air photos, TLS, Lidar, photogrammetry, use of drones).

Following this remark, we add new details: “Since Sunamura (1992)’s compilation, 26 years ago, many new quantitative studies have been published. They took advantage of several technological changes in that time interval. National mapping agencies released their aerial photography archives online, allowing to record cliff top retreat along decades. These provide contemporary surveys with a historical context. Airborne and terrestrial lidar as well as structure-from-motion (sfm) have revolutionized ad hoc surveys in geosciences, making precise geometric information available where and when required. Those methods allows to record rockfalls from cliff face and assess their volumes. Software developments afforded massive 3D processing capabilities, even to non-specialists. So quantitative site studies are now addressing cliff face erosion style at centimetre-scale (e.g., Dewez et al., 2013; Earlie et al., 2015; Gulayev and Buckeridge, 2004; Letortu et al., 2015; Rosser et al., 2007; Young and Ashford, 2006). This high spatial accuracy is nowadays added to high time resolution up to 20 minutes with detection of decimetric fragments from cliff face Williams et al. (2018). Cliff recession phenomena have never been so well defined in space and time. It is now time to sort through possible processes generating cliff responses.”

Page 3

Line 1: 'high time resolution of up to 20 minutes' – it would be helpful to say what this high temporal resolution data records – removal of individual small rock fragments from the cliff face?

Done, see precedent paragraph.

Line 5: 'study their relative efficiency'- not clear how this relates to linking erosion rates and external forcings – perhaps amend sentence to improve clarity.

The amendment was done, the sentence was rephrased to: "This database is used in a new approach to link erosion rate and external forcings. It allows also to look for a relative efficiency of forcings between each other to explain erosion rates variations at global scale. "

Line 8: 'reduces information to the largest common denominator' – yes, this may be a limitation but it is also an opportunity! It would be helpful if the paper can set out, on the basis of this study, a clear statement of the scale/resolution of study and also the important factors to record for future studies of rock coast erosion – in order to improve the resolution of the GlobR2C2 in the future. We added a new section (4.2.5) in the paper indicating which efforts must be made for future studies. Line 18-19: it woud be helpful to say here what databases are used.

Done, explained in section therein.

Line 27-30: sentence beginning 'It helps and the next sentence could be made clearer. For example, I am wondering if the conceptual exercise really minimises data capture? Should it be 'maximise data capture and minimise data redundancy'?

We made particular efforts in improving this paragraph. It becomes: "Merise provides a formal methodology to describe entity-relationship data models. Each entity corresponds to a group of data framed into a table and containing different fields. The different entities are related with each other by well-defined relations. As an example the cliff entity contains information about cliff settings. Each cliff description corresponds to a line in the cliff table and contains a unique primary key to identify this line/record. The measure entity contains information about cliff erosion. Cliff and measure are related through cliff erosion. The relation between an erosion record and its corresponding cliff is made by typing the cliff primary key. This conceptual exercise allows to minimize data typing and data redundancy, to flag possible information replicates and limits ill-conceived relationships. The database structure was implemented in OpenOffice Base that can be processed in R via SQL queries. Only the geographic fields (cliff location) were digitized in GoogleEarth and exported into shapefile with a key code or primary key linked to the relational database (in the sense of data science analysis)."

Page 4

Line 8: three types of sources? Are the data from scientific papers really raw data? Not clear what is meant by gridded data and tidy covariates.

The raw data, in the sense of database design, corresponds to the information encoded into the database with as little modification as possible from the original source. The publication itself is not a raw data, but in our database we took the information from it as raw data because they are not modified from the source. The second "raw data" type are the data extracted from global reanalysis grids: the grid values are recorded in GlobR2C2 without modification. Finally, we computed physical values from other fields values. Those newly computed quantities are encoded as new fields. Data scientists call them "tidy covariates".

Par beginning line 9: this could usefully be expanded to aid explanation. For example, is the method of measuring cliff erosion recorded and the time period over which it is measured? Figures will need to be re-numbered in order to ensure that they are referred to in the correct order.

A more detailed explanation of what is captured in each field is given below.

Section 2.3.2

Cliff lithology and description: it would be interesting to know how you have dealt with composite cliffs in the database – for example, a composite cliff may contain materials of different hardness/resistance at the toe and so marine forcing may be of reduced importance in such cases.

Information about composite cliff was implemented in the database. The lithology entity contains a lithology name and a field called “lithology location”. This field was filled with the information “toe”, “head” or “everywhere”. Composite cliffs represents 15% of records. In turn, only one erosion rate was associated with each cliff.

Page 5

Line 2 – 4: meaning unclear and it would be helpful to recast these two sentences to improve clarity.

These sentences are improved as: “They were characterised with a Boolean value (True/False) to be integrated in the database. True refers to the presence of fracturing/weathering mentioned in the paper. False means either that authors describe fracturing/weathering as non existent/negligible or is not mentioned in the paper.”

Line 7: not clear what is meant by ‘a primary key’.

See database design.

Line 10: etc. – please specify what is included in the etc.!

We specified : “The measure entity contains the erosion rate values and measurement methodology (how erosion was measured, for how long, with what threshold).”

Line 14: suggest amending to ‘estimates of volume loss to precise measurements using, for example, lidar

The amendment was done.

Line 15: suggest amending to '(iii) spatial extent along the coast

The amendment was done.

Line 23: not clear what is meant by 'the oldest method is rockfall inventory'

We reworded in 'Initially, 3D assessment were performed based on observable, large, rockfall scars or debris apron (e.g. ...'

Line 29: suggest amending to 'but with two caveats'

The amendment was done.

Line 31: it would be helpful to say how data were 'specifically treated' beforehand in order to prevent bias.

As it is the topic of an entire section in discussion we now make reference to it.

Page 6

Line 3: is it the case that faster eroding cliffs are more often sampled are more densely populated cliffs not also more often sampled by regional/national authorities?

We don't write that faster eroding cliffs are more densely populated but that authority fund more often densely populated and/or fast eroding cliff sections.

Line 7: suggest amending to that quality of photographs limits

The amendment was done.

Line 11: not clear what is meant by and produce wetting drying cycles does this mean, influences the vertical extent of wetting drying cycles on the cliff face? How about any potential influence on groundwater levels in more porous rocks?

We rephrased in order to be clearer: "The tidal range describes the variation in height of the water surface. A consequence is that the cliff and platform undergo cyclic wetting and drying that weakens and erodes the constituting rocks (Kanyaya and Trenhaile, 2005).”

Line 13-14: it would be helpful to add some explanation to the harmonics.

The amendment was done.

Line 29: time steps

The amendment was done.

Line 30: spelling – below.

The amendment was done.

Page 7

Line 17: thus, 3D measures (rather than this?)

Changed to ‘the 3D measures’

Page 8

Line 12: Fig. 9 is referred to but the last Fig referred to was Fig 5 – Figs 6, 7 and 8?

In order to keep the figures at the best position in the paper we removed reference to Fig.9 here.

Section 2.4.4:

It would be helpful to have some more contextual detail on the Hoek and Brown rock resistance classification that is used in the study.

This is done. We produce a new table (Table 11) and changed the text as: “Hoek and Brown (1997) describe field estimates of rock strength and experimental uniaxial compressive strength. They describe seven grades of rock resistance, from extremely weak to extremely strong. The table describing field estimates, resistance term, compressive strength and example is given in table 11. This table is associated with our Hoek and Brown classification and associated lithologies found in the database."

Page 9.

Line 6: Fig. 4 is out of synch.

Line 8: suggest amend to 1990s for every type of method'

The amendment was done.

Line 15: 6.4 km

The amendment was done.

Line 26: provide the number of observations for each class rather than just one.

The amendment was done. "Hard rock (341 observations) erodes at a median rate of 2.9 4 cm.yr-1 with a Median Absolute Deviation (MAD) of 3.4 cm.yr-1. Medium resistance rock coasts (63 observations) erode at around a median value of 10 4 cm.yr-1, with a MAD of 7.8 4 cm.yr-1. Due to the small number of observation of 10 medium resistance rocks, this resistance class should be considered carefully. Finally weak rocks (403 observations) erode at with a median value of 23 4 cm.yr-1and reach rates higher than 10 4 cm.yr-1with a MAD of 25 4 cm.yr-1."

Page 10

Line 17: 'amount of rainfall.'

The amendment was done.

Line 27: 'design allows an assessment of the drivers of erosion'?

The amendment was done.

Page 11

Section 4.2.1 See also Michoud et al. (2012) who estimated cliff retreat of the

“Dieppe landslide”: ‘activated on 17–18 December 2012 we measure a cliff retreat up to 40 m along two active scarps over 70 m wide’ (p. 415).

Indeed, it is another good example. We however did not include it because our first example is sufficient and well documented for our purpose.

Page 12

Line 10: ‘this finding reflects’ (remove is)

The amendment was done.

Line 29: amend TABLE

The amendment was done.

Page 13 It would be helpful to have some discussion of the importance of weathering that can be drawn on for the conclusion. It would also be helpful to make some recommendations for future studies of rock coast erosion that would help to address the data gaps identified in the compilation of GlobR2C2.

Such a paragraph has been included in the current version of the paper (section 4.2.5).

Figures

Figure 1: suggest amend to is similar to that

The amendment was done.

Figure 2: diagram a could usefully show the shore platform; there is no mention of faulting in the cliff settings – if it is included then it would be helpful to mention it; not clear what is meant by ‘aquiferous’ in the continental forcing. Diagram b seems to use only half of the 58 studies that are used in the database (there are 23 dots on the graph). Also, it is not clear what is meant by the ‘authors point of view’. It would be helpful to have some more explanation either in the caption or in the text.

The graph and its caption is modified to include shore platform and your remarks. The diagram b doesn't show all the studies used in the database but only the ones whose authors interpret and point out the erosion causes in the abstract.

Figure 6: Hoek and Brown

The amendment was done.

Figure 8: typo after temperature

The amendment was done.

Figure 9: Woodroffe

The amendment was done

Bibliography:

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