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Interactive comment

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

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We are grateful to Larissa Naylor (reviewer 1) for her very positive and insightful comments that helped improve the paper. We agree with her view that the paper was too focused on rocky coast and we add more context and links with shore platform evolution and geomorphic context.

General Comments

This paper presents a much improved, extended and comprehensive database of global coastal cliff erosion which brings together the rapidly expanding number of papers in this field, in a rigorous and comprehensive analysis. Of particular import is that their analysis allows for improved understanding of the impor-

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tance of rock resistance over lithology or climatic parameters as the key factor controlling erosion rates. They found that rock mass properties like joints and fractures are a fundamental control of coastal rock cliff erosion rates. They have come to these conclusions through creating a thorough, rigorous and repeatable database that can be extended through time as more papers are published. It is thus of great scientific importance and serves as a valuable tool which can be built upon. The authors are to be highly commended for their efforts. I really enjoyed reading this manuscript and once a moderate level of corrections are made, this will make a superb and much needed contribution to the literature. The key areas for improving this manuscript lie in six areas:

a) Improving the explanation of your methods and statistical analyses. Why did you use the tests you did? Which aspects did you test statistically?

For the purpose of this paper, we chose to follow a classical exploratory data analysis (EDA) scheme. An EDA is a prerequisite before embarking on more sophisticated methods such as machine learning algorithms. Machine learning classification and prediction is on our agenda and has been partly but we keep these results for a future paper. In the present paper, we tested the relation between a dependant variable (erosion rate) and (supposed) independent variables (external forcings). The relations between forcings was explored through principal component analysis. They appeared to be often strongly correlated. Concerning relation between erosion and continuous values, the non-normal distributions make us choose a non-parametrical approach. Spearman's rank correlation was chosen to evaluate the monotony of the relation.

b) Considering 'dating techniques' as an additional category of how erosion is measured and adding this category into your analysis (eg Figure 5) or explaining where this content best fits in your classification from 1D to 3D studies.

Erosion rates measured with Âń dating techniques Âż were encoded into the database (e.g. Choi et al., 2012; Hurst et al., 2017; Regard et al., 2012) . However we choose not to include them in the analysis because they don't represents the same processes and are dependent of eustatic variations. Those studies are generally transect type and would be classified as "1D" techniques.

c) Threshold, non-linear behaviour of coastal rock cliff erosion. Many of the types of cliffs included often display threshold-driven, non-linear behaviour. Whilst I appreciate you needed to standardise your reporting of erosion to mm/yr-1, I also wonder if it is possible to evaluate the degree of stochasticity /non-linearity in the database. For example, it may be that certain rock resistance types are more prone to non-linear, stochastic erosion events or that the temporal frequency between erosion events varies by rock resistance category or another parameter. Finding a clever way including this alongside your mm/yr-1 would improve awareness of the behaviour of these systems for risk managers, hazard scientists and geomorphologists alike.

The question of stochasticity/ non-linearity of erosion is an interesting one. However, it is difficult to approach it with our database. In fact, the major part of our data corresponds to averaged erosion rates over decades, mainly computed through comparison of aerial photographs. Evaluating the non linearity would need a more regular temporal monitoring of cliffs. This kind of approach is only really possible since lidar and SfM methods have become available to examine cliff face erosion. These techniques go back 10 years ago, which is a very short period of time to convince oneself that non-linear behaviours were reliably observed. Then, threshold detection requires frequent surveys for a long duration in order to build rockfall scar inventories. This is a lot of scientific effort to sustain acquisition, consistent processing and funding over time. Only very few scientific teams have been able to do this so far. The most prominent one is probably Nick Rosser's group in Durham, UK with whom we have started to collaborate.

One way to evaluate the non linearity is to explore magnitude/frequency laws. Those laws appears to be power law and have been explored for rockfalls, specially for continental cliffs (Barlow et al., 2012; Brunetti et al., 2009; Dussauge et al., 2003; Dussauge-Peisser et al., 2002). One way to evaluate the different stochasticity of rockfall could be to compare the coefficients of those power laws. However, the coefficients appear to be highly dependant on the observation duration (Dussauge-Peisser et al., 2002), spatial and temporal resolution (Williams et al., 2018).

In short, it is a very insightful question to which we cannot respond in a satisfactory fashion. We nevertheless aknowledge the question of rockfall stochasticity in section 2.4.1 Integration of punctual records, and further discuss it in 4.2.1 Erosion rates, study duration and stochastic behaviour.

d) Wider context. In places, the analysis and discussion of this paper is too narrowly focussed on coastal rock cliff erosion, rather than drawing on evidence from recent shore platform research which displays similar trends around the importance of geological contingency, the importance of rock mass properties and weathering/rock breakdown (bio/chem/phys) processes helping prepare rock coast landforms for erosion. This includes the early conceptual models of cliff erosion by Sunamura as well as recent papers on rocky shore platforms.

We added a last paragraph in discussion 4.2.4 Cliff retreat vs platform evolution and rock coast erosion. We also improved fig. 2 to show the platform more explicitly.

e) Figure 1 and your discussion of it shows the importance of the wider geomorphic context in influencing erosion rates. This does not appear to be taken into consideration in the current version of your model. It would be useful for the authors to explore how this may be possible, so that a global analysis of how submarine to cliff-top coastal landforms vary around the globe and how this affects erosion rates. For example, what proportion of cliffs globally are currently shielded by offshore features such as those in part of Figure 1? Does this vary by rock resistance of the cliffs or are other factors influencing this? I realise that much of this may be beyond the scope of your current paper, but it may be use-

ful to signpost this in your current paper, perhaps using data from both parts of Figure 1 as an example to illustrate how cliff erosion rates are modified by their wider geomorphic context, and thus are partly geomorphologically controlled.

We agree that taking wider geomorphologic context would add a lot to the model. Currently, with the notable exception of cliff height, we don't take geomorphology into account neither for the cliff nor submarine geomorphology. It would be a big challenge to take it into account for two main reasons. The first one is to find appropriate geomorphologic descriptors that make consensus across the community, or propose our own, which could be regarded as a curiosity. The second challenge is to find available auxiliary data to get those descriptors consistenly for all sites.

f) Lastly, it would be useful to signpost the wider significance of your work for coastal hazards scientists, geologists and in the context of changing storminess and sea level rise. It also would be helpful to highlight the potential to extend the database to include shore platform erosion rates. This would help show the wider relevance and import of your work. Ok, this was done in section 4.2.5 Toward a new rocky coast cliff research agenda

Specific Comments (SC), Technical Comments (TC)

Title

SC - You may wish to change the title to better capture the global database /analysis that is, to me, a significant strength of your paper and a very strong addition to the literature.

Thank you for this advice. The title was changed to: "GlobR2C2 (Global Recession Rates of Coastal Cliffs): a global relational database to investigate coastal rocky cliff erosion rates variations."

Abstract

SC - Show the wider relevance of your important work here

We added a final sentence to allude to several impact of this research:

In this first version, GlobR2C2, with its current encompassing vision, has broad implications. Critical knowledge gaps have come to light and prompt a new coastal rocky shore research agenda if one day we hope to answer such questions as coastal rocky shore response to sea-level rise or to increased storminess.

Introduction:

TC - First sentence needs reference and second sentence needs a direct quotation.

We added reference to Moses and Robinson (2011) for the first sentence.

SP – wave-cut vs shore platform needs a little more discussion

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 add some sentences within the introduction to better articulate between the shore platform and rock coast erosion.

TC – para 25 Fig 3 or Fig 5?

The figure reference was removed here.

TC – para 30 cite Viles 2017 Geomorphology

This reference was added

Method:

SC – define your boundary conditions and cite Kennedy who first used this term explicitly in rock coast geomorphology

Changed to

”However, marine and continental forcings conditions are often reported in a very heterogeneous fashion.”

SC – systematic search method needs improving, this can either be quite simple as per Figure 1 in Naylor et al. 2010 or following the more detailed PRISMA method (Moher et al. 2015) stemming from medical science.

We did not understand this comment

TC – Merise needs a year, pg. 3 para 25

The reference is Tardieu et al. (1985)

SP – pg 4, Para 10 sentence 1 examples adding would be helpful to aid understanding of your database.

In order to improve clarity, an example was added as the first paragraph of section 2.2 Database design. “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.”

TC – pg, 4 para 5, first sentence could be reworked

The wording was deliberately casual but we rephrased it as required in section 2.3.2 Cliff and lithology description

Cliff geology may exhibit a possibly very complex set of lithologic types, contact relationships, inherited tectonic structures and overprinted weathering and authors. . .

SP – section 2.3.1. a) Only English is mentioned here but Spanish and French is mentioned earlier. B) define your search method and strings (perhaps as supplementary material), this will make this part of your work reproducible and improve rigour.

a. Peer reviewed articles are in English and Âń white literature Âż is in English, French or Spanish b. Our search method was :

- We started from a corpus of articles identitified by an early undergrad student's work
- The references cited in this initial set of articles we then explored
- Searches where then launched in bibcnrs (national French research center bibliography engine) with keywords "erosion", "sea", "cliff", "rocky"
- Finally, this was completed with an email call to the coastal community via "coastal list"

This procedure may not be as rigorous and reproducible as Naylor would have wished for. But even if it is an organic growth of knowledge, the corpus of data is now contained and structured in GlobR2C2 and any new reference can be checked against existing records.

SP – 2.3.4 add Hurst et al. 2017 as reference for 1000s of years scale

The citation was added.

SP - 2.3.5 last sentence is unfinished

Sentence was completed: "We discuss this choice in discussion section."

SP – 2.3.9 can you validate your assertion in the last sentence?

The first attempt at global scale has been verified to be satisfactory (sentence before), but we cannot estimate the accuracy of cliff height indicated in the publications (maybe on the order of 10 meters).

SP – 2.4.4 Not all of your core readers will be familiar with the Hoek Brown criterion as it is a geotechnical/engineering criteria. I recommend you add some

background information and some rationale for why this was the best metric to use. Here it would be good to explain why Selby 1980 is less suitable than Hoek Brown.

This is done. We produce a new table (Table 1) 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 1. This table is associated with our Hoek and Brown classification and associated lithologies found in the database."

Section 3:

SP – 3.3 See comment above about dating methods.

SP – 3.4.1 fewer medium resistance rock studies, perhaps make this as a suggestion for future research in your conclusions, along with the present geographic limitations?

The few records concerning medium resistance rocks is due to several reasons: 1. Medium resistance rocks concern a smaller spectrum of rock types than weak and strong ones (see table 1 for unique lithological names). Weak resistance rock varies from extremely weak (can be peeled with a nail) to weak. Our weak and strong rocks actually aggregate 3 class of Hoek and Brown criterion (extremely/very/ weak, and equivalent for strong) (see table 1). 2. The large majority of erosion rates in hard rock cliff is brought by the systematic survey of CEREMA along the French coastline (265 values over 343, 77%). Despite these justifications, we added a mention of this objective I section 4.2.5 Toward a new rocky coast cliff research agenda

Section 4:

SC- Para 5, page 11 - more detail on this conference, a specific pers comm would help here too.

We cannot locate to what this comment refers to .

SC- Weathering, jointing, discontinuities – Sunamura included these parameters in his early conceptual models of rock cliff, rock coast and shore platform erosion, showing how they contributed to the reducing the resisting force of rocks. The influence of these on erosion processes and rates has been more recently discussed for rocky shore platforms (See Cruslock et al. 2010, Naylor and Stephenson, 2011, Stephenson and Naylor 2012) and biology (Naylor et al. 2012).

The citations are added.

SC - 4.2.1 para 20, this is where the threshold, non-linearity comment above relates.

SC - 4.2.3 pg 12, para 10, I recommend you refer to Kennedy et al. 2014 here as this volume has no chapter on Africa, which accords with your analysis of rocky cliffs. Doing so would strengthen this point.

The reference to Kennedy et al. 2014 was added.

SP – pg 12, para 20, does this mean it relates only to softer rocks? Please clarify.

The paragraph was modified to be clearer: "Studies also focus on fast eroding coasts because they represent bigger risks and also because of methodological limitation. Indeed, the French CEREMA study brings the majority of erosion values for hard rocks (265 values over 343, 77%) and medium rocks (47 values over 66, 71%). Without this systematic study soft rock represents 75% of measured cliff retreat. This fact biased the analysis by mostly documenting erosion distribution in higher values. The weight of this bias can be approached thanks to the French CEREMA study."

TC - Pg 12, para 25, I think this is table 2?

The reference was table 2, the text was modified.

SC - Page 13, para 25 there are many newer rock coast evolution models including consideration of the impacts of climate change (e.g. Limber, Ashton, Trenhaile) that are worth looking at to improve your link to modelling.

We just indicated some examples here. We added a citation to Limber et al. (2014).

Technical comments for the whole the Manuscript: Minor improvements to your English is needed occasionally throughout the manuscript The manuscript has be minutely checked for English. Measure often needs to be measurement

The text was checked to correct this.

Page 13 – inshore could be confused with 'inshore waves'; I recommend using terrestrial instead.

This amendment was done

Page 20, what does Q83 refer to? To the 83% quantile, modified. Also add a final sentence, or extension to it that shows which rock categories this relates to.

In a few places you talk about rocky coast erosion, your topic is coastal rocky cliff erosion. For clarity about your scope and the contents of your paper, the latter term should be used throughout. Your remark was taken into account and the term coastal rocky cliff was used.

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~~How~~ GlobR2C2 (Global Recession Rates of Coastal Cliffs): a global relational database to ~~explain variations in sea~~ investigate coastal rocky cliff erosion rates ~~? Insights from a literature synthesis~~variations.

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Abstract.

Rocky coast erosion (i.e. cliff retreat) is caused by a complex interaction of various forcings that could be marine, subaerial or due to rock mass property. ~~It turns into variable erosion rates (~~From Sunamura's seminal work in 1992, it is known that cliff retreat rates are highly variable over 4 orders of magnitude at least, from 1 $\mathrm{mm.yr^{-1}}$ to 10 $\mathrm{m.yr^{-1}}$~~)~~. While numerous local studies exist and explain erosion processes on specific sites, there is a lack at global scale. In order to quantify and rank the various parameters influencing erosion rates, we compiled existing local studies in a global database called GlobR2C2 (for Global Recession Rates of Coastal Cliffs). This database records erosion rates from publications, cliff setting and measurement specifications; it is filled from peer reviewed articles and national databases. In order to be homogeneous, marine and climatic forcings were recorded from global models and reanalysis. Up to now, GlobR2C2 contains 58 publications which represents 1530 cliffs studied and more than 1680 erosion rate estimates. A statistical analysis was conducted on this database to explore links between erosion rate and forcings at global scale. Rock resistance, inferred through Hoek and Brown (1997) criterion, is the strongest signal explaining variation in erosion rate. Median erosion rates are of 2.9 $\mathrm{cm.yr^{-1}}$ for hard rocks, 10 $\mathrm{cm.yr^{-1}}$ for medium rocks and 23 $\mathrm{cm.yr^{-1}}$ for weak rocks. Concerning climate, only the number of frost days (number of day per year below 0°C) for weak rocks shows a significant, positive, trend with erosion rate. ~~Every other relations with both~~ The other climatic and marine forcings ~~are very spread and non-significant.~~ do not show any clear and significant relation with cliff retreat rate. In this first version, GlobR2C2, with its current encompassing vision, has broad implications. Critical knowledge gaps have come to light and prompt a new coastal rocky shore research agenda if one day we hope to answer such questions as coastal rocky shore response to sea-level rise or to increased storminess.

1 Introduction

Rock coasts are characterized by dynamically linked cliff retreat and shore platform erosion (Moses and Robinson, 2011). By comparison between continental and coastal cliffs, it is clear that the presence of the sea is a fundamental driver of cliff retreat (Fig.1). But, as Moses and Robinson (2011) felt, "our understanding of their dynamics and our ability to predict their evolution over time remains severely limited". Kennedy (2014) emphasize emphasizes the growing number of quantitative studies, allowed by the development of new investigation methods like lidar techniques. According to their analysis, a reassessment of cliff retreat rates is needed. Hence, the purpose of this paper is to take advantage of this growing corpus of data in order to quantitatively analyse cliff erosion drivers.

These drivers can be divided in three groups, depending on their nature (Fig.2). The first group of drivers concerns marine forcings. Waves attack and weaken cliff base, sometimes carving a notch, leading to cliff instability and subsequent collapse (e.g., Benumof et al., 2000; Caplain et al., 2011)(e.g. Benumof et al., 2000; Caplain et al., 2011). It is a common assumption in coastal landscape evolution model and led to the debated term 'wave cut platform' (Anderson et al. , 1999)development of a shore platform below the cliff. It has sometimes been described as entirely shaped by the waves, leading to the dabated term of 'wave cut platform' (e.g. Anderson et al., 1999). The reality is more complex (see thereafter); we prefer the term of '(rock) shore platform'. Debris aprons are then removed by sea action, allowing for renewed wave attack at cliff base. Cliff base weakening, cliff collapse and debris apron removal, before renewed cliff-base weakening can be called platform/cliff erosion cycle (e.g. Caplain et al., 2011). Wave assailing force depends on wave energy dissipation over the shore platform (e.g., Sunamura, 1992; Trenhaile, 2000)(e.g. Sunamura, 1992; Trenhaile, 2000). The wider and shallower the platform is, the lower is the remaining wave power at cliff foot. Hence platforms can be regarded as natural defences against wave attack to the cliff. The shore platform is evolving under marine forcing like , wave agitation and associated shear stress (e.g., Sallenger Jr et al., 2002; Ste or tide-induced wetting and drying cycles (Kanyaya and Trenhaile, 2005; Stephenson and Kirk, 2000). The second group of drivers is rock mass properties that are supposed to have a strong influence on cliff evolution (Mortimore and Duperret, 2004). The rock mass behaviour depends on its lithology, structure, fracturing and weathering (e.g., Cruslock et al., 2010)(e.g. Cruslock et al., 201 The third group of drivers is made of subaerial processes. Climate through precipitationsprecipitation, temperature or frost occurences (e.g., Dewez et al., 2015) (e.g. Dewez et al., 2015) may either provoke cliff instability or prepare for it by physical and chemical weathering (Duperret et al., 2005).

All these have been proven to be efficient in their own way in cliff retreat phenomena, but their relative importance is perceived differently in the studies (Fig.2), likely because of the small spatial extent of the sites or the authors' field of expertise. Some attempts exist at local scale to rank the different drivers (e.g., Earlie et al., 2015; Lim et al., 2010) (e.g. Earlie et al., 2015; Lim et al., they can hardly be upscaled.

Some studies aimed at quantifying cliff retreat rates at the regional scale i.e. coastal sections of several tens to hundreds of kilometres(e.g., Gibb, 1978; Abellán et al., 2009; Hapke et al., 2009; Moses and Robinson, 2011; Perherin et al., 2012). In terms of retreat drivers, they are inconclusive . 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). This implies that those studies cannot be used to describe global retreat drivers because : (i) they do not analyse the contribution of each driver; and , (ii) they remain too local and characterise a narrow range of forcings (e.g. climate, homogeneous lithology . . .)

In order to pass through bias biases inherent to individual approachapproaches, studies at global scale have been conducted. They are often based on qualitative morphometry. For example, the classic study of Emery and Kuhn (1982) interprets cliff profile morphology as a function of cliff top and toe composition and marine and subaerial relative process efficiency. The only global, quantitative, data set was produced bySunamura (1992), on the basis of quantitative studies published prior to that date. Sunamura's database was only used by Woodroffe (2002) to evaluate ranges of erosion rates for different lithologic type. Up to now, those rates have never been related to environmental factors.

Since ~~Sunamura (1992)~~Sunamura's 1992 compilation, 26 years ago, many new quantitative studies have been published~~(Fig. 5).~~ . 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~~SfM) have revolutionized ad hoc surveys in geosciences, making precise geometric information available where and when required ~~. National mapping agencies released their aerial photography archives online. These provide contemporary surveys with a historical context.~~ (Viles, 2016). Those methods allow 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 Ash~~ This high ~~spateial~~ spatial accuracy is nowadays added to high time resolution up to 20 minutes ~~Rosser (2016)~~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.

We updated Sunamura (1992)'s data set into the new database GlobR2C2, for Global Recession Rates of Coastal Cliffs, by taking ~~the benefit~~ advantage of all the existing ~~case~~ site and regional studies and built a worldwide cliff recession database. This database is used in a new approach to link ~~erosion rate~~ documented erosion rates and external forcings~~and study their relative efficiency~~ . It allows also to look for a relative efficiency of forcings between each other to explain erosion rates variations at global scale. The benefits of this global approach is to erase local ~~specifies~~ specificity and to look at global trends. The links between cliff retreat and environmental parameters were explored statistically. The synthetic database approach however has the limit that it compiles the information available for all studies at once. In that sense, it reduces information to the largest common denominator. The main goals of this paper are therefore to: (i) make a review of online literature in English, French or Spanish language from peer-reviewed or national ~~database~~ databases providing cliff retreat rates; (ii) link a dependent variable: erosion rate to independent variables: cliff and meteo-marine settings. The analysis demonstrates the predominance of factors leading to cliff retreat.

2 Method

2.1 Study design

The main goal of this study is to link ~~erosion~~ cliff retreat rate to external forcings at global scale. Those data exist in peer reviewed journal articles and national databases. Peer reviewed articles were chosen to be the source of cliff description and erosion rate value and settings. However, ~~boundary~~ marine and continental forcings conditions are often reported in a very heterogeneous fashion. ~~Those~~ This information can either be completely lacking, incomplete or can be described in very heterogeneous ways. To overcome this issue, external global database were used to homogenise forcings ~~.~~ (i.e. tidal range, swell height, rainfalls etc. see sections 2.3.6 to 2.3.9). They provides homogeneous and reputable information for cliff height, sea condition and atmospheric climate.

The different steps of the study that are going to be described in the next paragraphs are: (i) creation design and filling of a database relationaldatabase with raw data, (ii) post-processing on database fields in order to tidy up the data (iii) statistical exploration of links between erosion and forcings.

2.2 Database design

To organise the disparate knowledge reported in the literature, a rigorous analysis framework is an absolute necessity upstream of any data capture. We opted for a relational data base framework whose architecture was conceived designed according to the Merise method (Tardieu et al., 1985). Merise provides a formal methodology to describe entity-relationship data models. It helps conceptualize data groups (entities), their properties (fields), specifying the existence of relationships between tables, their direction (one-way, two-way, origin and destination) and their number (one entry relates to one or to multiple entities). Each entity corresponds to a group of data framed into a table and containing different fields called attributes. The different entities are related to each other by well-defined relations. As an example the *cliff* entity contains information about cliff settings (Fig. 3). 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 optimize data capture 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 addressed by the statistical software 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).

Here, data GlobR2C2 was structured with two objectives in mind: (i) compiling original information and faithfully tracing publications sourcepublication sources, and (ii) anticipating analytic queries of the database designed to answer geomorphological questions. The database is structured to keep track of information relative to publications, sites, measurements and contextual information of the cliffs, or their environment. Specific care was taken to separate original data from information derived by us, and distinguish between article information from auxiliary data sets . (Fig. 3). The database contains entities coming from tree type of sources: raw data from paperspublications, raw data from gridded data (global reanalysis) and tidy covariates (derived from raw data).

The final conceptual data model contains 11 entities and 76 attributes. A conceptual model is given in (Fig.3). Entities refer to publications (*Publication and Author*), cliffs (*Cliff, Lithology, Geotechnical parameters, cliff Cliff height*); erosion rate measure measurement (*Measure*) and to forcing (*Climate, Swell, Tide*). Information contained in each entity come from publication except entities concerning forcings and Geotechnical parameters *Geotechnical parameters* which come from external sources . (Fig. 3). The relation between the different entities are given explicitly described by the action verbs and the numbers represents the cardinality of the relation (eg. 1 cliff can correspond corresponds to 1 or N erosion rate measuremeasures, cardinality 1,N).

2.3 Database information fields

2.3.1 Raw data extraction: From publication and national databases

GlobR2C2 (Global Recession Rates of Coastal Cliffs) database v1.0 was populated with data coming from two main type of published sources: published peer-reviewed English journal articles, and official but non-peer-reviewed studies arising from official organizations (e.g. CEREMA French risk survey) in English French or Spanish language. Journal articles were selected when they proposed quantified value of cliff recession rates and described the quantification method. The search was initiated with bibliographic web search engines (Web of Science, Google Scholar) and expanded using citations therein. We admit that some references may have escaped our attention. We are keen to expand the database further with the contribution of the community. The version presented in this article is version 1.0. compiling references up to 2016.

2.3.2 Cliff and lithology description

~~Cliff and lithology~~ The *cliff* and *lithology* entities contains information relating to cliff ~~settings:~~ morphology (i.e. height, length~~,~~) and rock property (i.e. lithology, fracturing, weathering, folding, bedding~~etc.~~)

~~Describing the rocks of a cliff sector is a bit of a tricky issue. They may vary from place to place laterally and vertically. They may also be fractured or weathered differently and authors~~ Cliff geology may exhibit a possibly very complex set of lithologic types, contact relationships, inherited tectonic structures and overprinted weathering. Authors do often not apply a very strict formalism to report them. In front of the broad diversity instances, we synthesized information in the following manner. A lithological name fills the "lithology" entity and a position field records rock position along the cliff (~~head, toe or overall~~numbered from cliff toe to cliff top). Additional descriptions were copy/pasted in comment fields in order to preserve a trace of the original description. By comparison rock state (weathering, folding, faulting, bedding etc.), is rarely mentioned. This could be because the cliffs do not present any such characteristics, or because authors did not think relevant to mention it. Moreover, parameters describing rock state are either complex or technically expensive to describe and quantify or outside the authors' scientific field of expertise. They were ~~characterise~~ 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 otherwise.~~ . False means either that authors describe fracturation/weathering as non existent/negligible or is not mentioned in the paper.

2.3.3 Cliff location

Cliff location is entered as a geographic ~~information~~coordinates. Studied cliff site extent was digitized from ~~to~~ publication information and mapped using Google Earth. A primary key links this geographic file to the database.

2.3.4 Measure description

The measure entity contains the erosion rate values and measurement methodology (how erosion was measured, for how long~~etc.~~, with what detection threshold). Erosion is most of the time provided as an erosion rates in meters per year, occasionally as finite retreat (in meters), minimum and maximum erosion rate or eroded volume (in cubic meters).

Cliff retreat measurement errors and time spans were also recorded. Indeed, measuring sea cliff erosion presents a wide range of techniques. Those techniques vary largely in terms of: (i) accuracy, from field observation and "expert" estimates ~~(e.g., ?)~~ May and Hansom (2003) of volume loss to ~~lidar (e.g., Dewez et al., 2013)~~ precise measurement using for example lidar (e.g. Dewez et al., 2013) ; (ii) time period surveyed, from twenty minutes ~~(Rosser, 2016) to thousands years (Choi et al., 2012; Regard~~ thousands of years (e.g. Choi et al., 2012; Regard et al., 2013; Hurst et al., 2017); and (iii) Spatial extent along the coast, from tens of meters ~~(e.g., Letortu et al., 2015) to kilometres (Gibb, 1978; Hapke et al., 2009)~~ (e.g. Letortu et al., 2015) to kilometres (e.g. Hapke et al., 2009) Moreover, these measurements can be divided into three classes of methods: 1D, 2D or 3D.

1D cliff retreat measurement techniques correspond to retreats calculated on single transects. Typically, they correspond to ~~measure~~ measures done with peg transects recording the cliff toe retreat or transects on aerial photographs to quantify cliff-top retreat (Kostrzewski et al., 2015; Lee, 2008; Pye and Blott, 2015). 2D measurements are mostly based on aerial photograph comparison. They either quantify the area lost between two aerial photographs campaigns or average numerous transects (Costa et al., 2004; Letortu, 2013; Marques, 2006). 3D techniques record the evolution of the cliff face and quantify volumes ~~(e.g., Letortu et al., 2015; Lim et al., 2005; Rosser et al., 2007). The oldest method is rockfall inventory (rockfall volume estimation based upon size of debris or scar, (e.g., May, 1971; Orviku et al., 2013; Teixeira, 2006)~~ (e.g. Letortu et al., 2015; Lim et al., 200 Initially, 3D assessment were performed based on observable, large, rockfall scars or debris apron, (e.g. May, 1971; Orviku et al., 2013; Tei now the two most used methods are lidar and SfM.

2.3.5 CEREMA French national dataset: a particular case

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 ~~rocky coast)~~ coastal rocky cliff, it correspond to 465 (53%) values in the database). This rich systematic dataset was obviously included in GlobR2C2 but ~~raise~~ with two caveats. On the one hand, the CEREMA study introduces a strong spatial bias for French oceanographic and climatic conditions in the database observation records. This situation may risk to polarize analytical results but was recognized beforehand and specifically treated to prevent such bias ~~.~~ (cf. part 4.2.3).On the other hand, being a systematic study for every stretch of coastal cliff around the country, it makes it more robust to scientific and funding biases. Research funds are often sought for areas combining coastal threats with societal interest. Coasts with higher recession rates are therefore more often sampled, while quiet stretches of coastlines remain in the shadow. Including this data therefore provides a more representative set of values existing along coastlines. Among little studied sectors ~~it represents~~ this CEREMA study contains hard rock coastal stretches (e.g. hard Proterozoic granites from French Brittany) and erosion rates lower than the study's detection threshold.

Based on historical aerial photograph archives, CEREMA acknowledges that photographs quality to that quality of photograps limits the detectable cliff recession to rates higher than 10 cm/yr. Below this value, they deem recession rates as undetermined. We chose to record those undetermined values in the database but not to use them in the statistical analysis. We discuss this choice in the followingdiscussion section.

2.3.6 TideTides

The tidal range describes the water column height at cliff foot and produce variation in height of the water surface. A consequence is that the cliff and platform undergo cyclic wetting and drying cycles that weakens and erodes the constituting rocks (Kanyaya and Trenhaile, 2005). Rather than referring to difficult use tidal records from tide gages, tidal modelling was performed with FES 2012 software (Carrère et al., 2012). This model which gives all the constituents of the harmonic tide analysis. For our analysis, 8 harmonics were considered: M2, N2, K2, S2, P1, K1, O1. Those harmonics represents diurnal and semi-diurnal main component of tide harmonic model. The model produces time series between given start eand stop dates of sea water height within a regular grid of 0.25 degreebetween two dates. The tide is computed . Tidal characteristics were retrieved for each study location for two entire years, of which is extracted the mean amplitude over N two cycles (i.e. height difference between successive high and low tides).

2.3.7 Waves

Wave properties were extracted from ERA-interim reanalysis dataset (Dee et al., 2011). This gridded data has a pixel size of 0.75 degree. Temporally, data spacing is 6 hours during the 1979-2016 period. Wave assault was characterised both in terms of mean agitation and extreme events. Three mean parameters characterise wave assailing force: significant wave height of combined swell and wind, wave period and wave direction. For swell characteristics, mean significant wave height and wave period characterise the average sea agitation. The wave direction value records the most frequent wave direction for the duration of the reanalysis period (1979-2016).

Anticipating that mean sea state values may be deceptive metrics, a record of extreme events was also described. Those events were characterised by the 95 % percentile of wave significant height as suggested by Castelle et al. (2015). To complete this quantile value, the number of storms experienced at each cliff site was calculated between 1979 and 2016 according to (Castelle et al., 2015). 2016.

2.3.8 Climate

Climatic information was extracted from Climate Research Unit data between 1961 and 1990 Mitchell and Jones (2005)(Mitchell and Jones The grid size is 0.5 degree, at monthly time stepsteps. Chosen parameters likely to influence erosion rate are mean annual rainfalls, mean monthly temperatures and number of freezing days (number of days per year bellow below 0°C). We did not find a global climatic data set reporting time series of rainfall and temperatures spanning the durations covered by the articles contained in GlobR2C2.

2.3.9 Cliff height

Cliff height appeared to be often missing. Filling this value is not straightforward because cliff height can be strongly variable along the surveyed cliff. Nevertheless, in order to provide a robust estimate, a mean cliff height was extracted from the 8" global DEM (GMTED2010, Danielson and Gesch, 2011). Cliff height extraction consisted in computing a buffer around the cliff extension shapefile, in which the mean value of non-zero pixels (corresponding to the sea) is computed. To assess the accuracy of these cliff height estimates, they were compared against those rare values presented in publications. Computation is close to value given in publication with a root mean square error of 19 m at global scale. ~~It is quite good~~ We deem it sufficient for a first attempt at the global scale, probably not so far from the cliff height accuracy in the publications.

2.4 Tidying the covariates: from database fields to predictors

The first purpose of the database is to collate raw data from original sources in the most traceable manner. This data does not necessarily report information in an easily accessible fashion. This may be because: (i) fields translate different realities (e.g. recession rates vs retreat values or recession rates relate to profile-specific recession rate or to kilometre long cliff sections), (ii) value instances of a field is too broad and needs summarizing in fewer categories (e.g. lithology). Thus, post processing was applied to the database in order to make it more homogeneous and more readily usable for statistical analysis.

2.4.1 Integration of punctual records

We mentioned earlier that measurement techniques were either 1D, 2D or 3D. These methods do not reflect exactly the same processes and a choice was made to force all measurements to report 2D type measurements homogeneously. ~~This~~ The 3D ~~measures in~~ measurements in $\mathrm{m}^3.\mathrm{yr}^{-1}$ were divided by cliff face surface in a cliff top equivalent retreat in $\mathrm{m.yr}^{-1}$. 1D measurements do not average information ~~spatially~~laterally. Cliff retreat is a stochastic process in time and space and 1D measurements profiles may happen to quantify erosion on a ~~particular~~ particulary high or low erosion transect. Erosion rates of the transect ~~measures~~ measurements were therefore averaged for a unique study, cliff and period of time in order to limit the risk of over/under-representation.

2.4.2 Field unit conversion

Original data may be provided in different ways (for example the time span between 2 measurements may be given by a duration or start and end dates). As often as possible this information is summarized in a single duration field with homogeneous unit. This lists the operations performed:

- To obtain a duration in years, the fields measure duration [year], measure beginning and measure ending [date] were merged together
- Retreat [m] and eroded volume [~~m3~~m^3] were ~~normalised~~ converted to retreat rate [$\mathrm{m.yr}^{-1}$].

- The mean cliff height is either obtained from a cliff height mean field or as the mean between height min, height max [m].

- The error ([m/yr)] is a compilation of error value and error type.

2.4.3 Average site climate

Some explanatory variables were strongly correlated with each other (e.g. wave period vs wave significant height). This redundant information may lead to spurious correlation. New synthetic variables combine existing variables.

- Monthly mean temperature were converted into mean annual temperature and amplitude.

- Deep water swell energy flux was computed using swell period and significant height

$$E_f = \frac{1}{8}\rho g H_s^2 C_g \qquad with \qquad C_g = \frac{1}{2} g \frac{T}{2\pi} \tag{1}$$

  Where ρ is water density; Hs [m] is significant wave height; Cg [$m.s^{-1}$] is wave group velocity; and T [s^{-1}] is wave period.

- Swell direction incidence with respect to the cliff.

2.4.4 Rock resistance inference

The database, filled with information from publications, results in more than 40 distinct lithological descriptions. We first grouped lithology into 9 groups with a similar classification to that of Woodroffe (2002) for historical comparison(Fig. 9). . But lithology alone does not governs govern rock mass mechanical properties. Tectonic inheritance, deformation, fracturing and weathering weaken the rock masses. Consequently, the rock constituting the cliffs are divided into rock mass strength criteria. Following the practical examples from Hoek and Brown (1997), we propose to further aggregate Hoek and Brown's macroscopic rock mass strength categories into three categories. 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 1. This table is associated with our Hoek and Brown classification and associated lithologies found in the database.

Aggregation criteria are based on the fields lithology name, weathering, fracturing and comments, in which all published details on rock strength, structural geology, weathering were preserved. Rocks were classed into three resistance classes termed hard, medium and weak. One may note that a similar approach, but with two classes only, was adopted by the Eurosion project consortium (Doody and Office for Official Publications of the European Communities, 2004). Hard rock cluster together granite, gneiss and limestones. Weak rocks are mainly poorly consolidated rocks (weakly cemented sandstones, glacial tills and glacial sands) or strongly weathered rocks. Weak rocks noticeably include well studied chalk cliffs. Medium resistant rocks correspond to claystone shales and siltstones.

3 Analysis / Results

3.1 Database content, completeness

The database is filled with 58 studies, out of which 47 are peer reviewed articles and 11 are public national databases, documenting 1530 cliff sites and 1680 erosion rate records. Indeed, some cliff sites where repeatedly measured over different periods. With more than 90% of complete fields, the database is rather well filled. However, the constitution of the database highlights some generally lacking description. We mentioned previously the difficulty to find a description of cliff rock weathering and fracturing. Those fields are missing for 98.4% of records (corresponding to 53 publications).

3.2 Where was erosion measured?

Studies are mostly concentrated in Europe (42 studies, 1579 records), in Oceania, focused mainly on New Zealand (3 studies, 94 records) and Northern America (4 studies, 50 records). Asia (2 studies, 4 records) and South America (1 study, 1 record) are poorly represented. No literature was found for the entire African continent. This lack is confirmed by the absence of chapter about Africa in Kennedy et al. (2014). Study locations are plotted in ~~Fig.~~ figure 4.

3.3 How was erosion measured?

The number of studies is steadily growing since the ~~middle 1990es~~ mid-1990s (Fig.5), for every method types. Older studies exist and are present in Sunamura's database, however those papers were not available and/or cliff and measure description too poor to be encoded in our database. The ~~method~~ most used method is the comparison of aerial photographs or historic maps, which correspond to a 2D method easy to apply and allowing erosion evaluation spanning several decades. 43 studies used this method representing 50% of published studies and 88% of the records. The second most used method is 3D type, which has become common from mid-2000. It represents 19 studies (22%) and 5% of records. Finally, some other methods are occasionally used. The 1D methods represent 8 studies (9%), 3.5% of the records.

Reported studies describe coastal processes along 20 m to ~~6,.4~~ 6.4 km stretches of coastline. The median length is 600 m. Total survey duration vary from just 1 month to ~~7.1 ka~~7'100 years, but half the data lie between 56 and 63 years given the bulk of aerial photograph comparison studies.

3.4 Examining relations between erosion rate and forcings

The purpose of the database is to examine the relationships between erosion rates, sites conditions and external forcing. Those links were sought by means of exploration data analysis statistics.

3.4.1 Erosion vs rock mass properties

One of the first influent factor often pointed in literature is rock resistance ~~(e.g., Benumof et al., 2000; Bezerra et al., 2011; Costa et al., 200~~ Figure 6 shows erosion rate distributions for the three rock resistance classes based on Hoek and Brown criterion. Three distinct behaviours can be seen. Hard rock (341 observations) erodes at a median rate of 2.9 $\mathrm{cm.yr^{-1}}$ with a Median Absolute Deviation (MAD) of 3.4 $\mathrm{cm.yr^{-1}}$. Medium resistance rock coasts (63 observations) erode at around a median value of 10 $\mathrm{cm.yr^{-1}}$, with a MAD of 7.8 $\mathrm{cm.yr^{-1}}$. Due to the small number of observation of medium resistance rocks~~(63 observations)~~, this resistance class should be considered carefully. Finally weak rocks ~~erode at with~~ (403 observations) erode at a median value of 23~~cm/yr~~ $\mathrm{cm.yr^{-1}}$ and reach rates higher than 10 $\mathrm{m.yr^{-1}}$ with a MAD of 25 $\mathrm{cm.yr^{-1}}$.

Macroscopic rock mass strength classes, though possibly crude, exhibits the ordered behaviour expected by literature: weak rock erode faster than medium strength rock, and medium strength rocks erode faster than hard rocks. Central erosion rate values increase by a factor 2 to 3 from one class to the next.

These values are in agreement with Woodroffe's work (2002), but, even if those distributions are distinct, they are broadly spread and multimodal.

3.5 Erosion vs marine forcings

In order to explore the influence of sea aggression, several variables were implemented in the database describing mean sea agitation and tidal range, and sea agitation during extreme events. All the variables concerning swell are strongly correlated. Hence, only three independent marine parameters are analysed in the following scatterplots (Fig.7): tidal range, wave energy flux and number of storms.

All scatterplots appear to be widely spread and do not show simple linear relations. Indeed, Spearman's rank correlation coefficients, which evaluates monotonic relations between two variables, ~~based on value ranks, are low~~ are low 8. Furthermore, many tentative correlations cannot be trusted (p-value > 0.05). Those correlations and associated p-values are given in ~~Table 1~~Figure 8. Exploration of marine forcings indicate that none has an apparent effect on erosion rates, except a weak relation between tidal range and erosion rates suggesting higher erosion for tidal ranges between 1 and 3 meters (yet not visible for medium resistant rocks).

3.6 Erosion vs climatic forcings

Concerning climatic forcings, recession rates are compared to temperature variation, frost frequency and amount of ~~rainfalls~~rainfall. As for marine forcings, data is very scattered (Fig.~~8~~9). Frost day frequency and rainfalls shows a positive trend with erosion rate for weak resistance rocks. Poorly consolidated rocks represents the large majority of ~~type of rocks~~ rock type present in cold (>50 frost day per year) and rainy climates (> 1000 $\mathrm{mm.yr^{-1}}$) in the database. Only a few studies concern harder rocks under cold climate. However, even if a trend exists, data are really spread and Spearman's rank correlation coefficient is low (0.25 for frost, 0.07 for rainfalls). Mean annual temperature do not show any clear correlation with erosion rate.

4 Discussion

4.1 Comparison to previous studies

The GlobR2C2 database provides a quantitative overview of current ~~rocky coast~~ coastal rocky cliff erosion knowledge. This database is the first update since ~~Sunamura (1992)'s~~ Sunamura's 1992 seminal publication and adds 54 additional quantitative studies to the scientific debate. Its design allows ~~to explore~~ an assesment of the drivers of erosion. Historically, Woodroffe (2002) already tried to link erosion with lithology in a broadly reproduced graphic. This graph shows a clear pattern of increasing erosion rates with decreasing rock resistance. ~~GloabR2C2~~ GlobR2C2 updates this classic graph using the same lithological classification (Fig.~~9~~10). New knowledge does not change historical views, but narrow down assumed erosion rate ranges both towards lower and higher rates. We also observe that supposed hard rocks as granites or basalts can erode as quickly as $1\ \mathrm{m.yr}^{-1}$. This is because resistance to erosion does not depend on lithological category alone, but also on the degree of weathering, jointing, folding~~etc. This graph~~, etc (Cruslock et al., 2010; Stephenson and Naylor, 2011; Sunamura, 1992). Figure 10, presented at a conference with sedimentologists triggered deep-hearted reactions for the lack of rock classification robustness in their community. This result confirms the choice for a less debatable rock resistance criterion instead of lithology. This geotechnical criterion is not perfect either. It was inferred based upon authors' description of the cliff, thus it can include a part of interpretation and some degree of uncertainty.

4.2 What knowledge does GlobR2C2 compile?

The GlobR2C2 database is based on bibliographic references ~~plus~~ as well as models and reanalysis used as proxies ~~of~~ for forcings. Some ~~bias~~ biases are inherent to this kind of approach. The next paragraphs focus on different aspects of these limitations due to the use of: (i) ~~: erosion~~ cliff retreat rate as a proxy of erosion, (ii) the use of model and reanalysis as proxy of forcing, (iii) the use of peer-reviewed journals.

4.2.1 Erosion rates, study duration and stochastic behaviour

Statistical exploratory data analysis (known as EDA) is a way to dissolve local particularity into a global analysis. Nonetheless, including every quantitative study implies mixing rates measured with different methods, accuracy, spatial and temporal extents, which could be a source of bias. Erosion is a stochastic event: the fortuitous occurrence of a rare big event would influence the actual figure of the observed retreat rate. Rohmer and Dewez (2013) for instance, describe statistical indicators for testing the outlier nature of very large rock falls, with methods borrowed to hydrology, seismology and financial statistics. These indicators were applied to a chalk cliff site in Normandy (northern France) in Dewez et al. (2013). During the 2.5 years terrestrial lidar monitoring period, a massive 70'000 m^3 rock fall caused a local cliff top retreat of more than 19 m (Dewez et al., 2013). That is more than one hundred years' worth of average retreat in one event. Estimated annual cliff recession rate rose from ~~0.13~~ 13 $\mathrm{cm.yr}^{-1}$ to 0.94 $\mathrm{m.yr}^{-1}$, a seven-fold increase, just by including this fortuitous, and definitely unrepresentative event (Dewez et al., 2013). Further demonstration is brought by other studies covering the same site. Costa et al. (2004)

had estimated the recession rate to be ca. ~~0.15~~ 15 $\mathrm{cm.yr^{-1}}$ in 29 years from aerial photos. And Regard et al. (2012), using millennial recession rates from ~~10Be~~ ^{10}Be accumulated in flint stones exposed in the chalk coastal platform, obtained ~~0.11 to 0.13~~ 11 to 13 $\mathrm{cm.yr^{-1}}$ over 3'000 years.

GlobR2C2 therefore addresses the concern of non-representative erosion values by compiling all studies available online, and retaining information from all sites and survey periods. In doing so, the actual dispersion of recession rate values is preserved and allows for recognizing outlying values (Fig.~~10~~11).

4.2.2 Forcing proxies

While publication-derived cliff recession rates and cliff conditions could be forced into a coherent database framework, environmental forcings were so scarcely and heterogeneously documented that the same rationalization process was not possible on the publication basis alone. Instead, publicly available global climatic and sea conditions database were used. These databases present the advantage of being spatially and temporally continuous thanks to reanalysed climate and sea state models. Their principal limitation is their coarse-grained definition compared to site specificities. Nevertheless, they document external forcings (i) in a uniform fashion (regular spatial and temporal sampling steps), (ii) for the entire globe, and (iii) reflect forcing condition for durations spanning several decades. So, even if regional or continental data sets offer more resolved information in space or time, the global extent ensures that all cliff sites worldwide are documented uniformly.

4.2.3 Literature biases as future tracks to improve cliff evolution understanding

GlobR2C2's worldwide compilation shows that research in this domain is very active. A lot of quantitative data already exist. However, even if data coverage is somewhat global, publications turned out to focus mostly on a few western countries. This finding ~~is~~ reflects the strategy of literature search adopted: only international and national literature published in English, French or Spanish were compiled. Due to the language barrier, we are aware that studies in Russian, German or Japanese languages, among others, were unwillingly obliterated.

Spatially, our search strategy did not flag scientific literature on the evolution of African and South American cliffs. Cliff recession studies are apparently focused on the richest areas where economically valuable coastal assets are exposed to losses. This geographic distribution induces an over representation of temperate climates and a limited presence of some extreme climates or wave condition like equatorial or polar regions. Those extrema could nevertheless be a key for understanding effects of climate and wave conditions on cliff erosion.

Studies also focus on fast eroding coasts because they ~~represents~~ represent bigger risks and also because of methodological limitation. Indeed, the French CEREMA study brings the majority of erosion values for hard rocks (265 values over 343, 77%) and medium rocks (47 values over 66, 71%). Without this systematic study soft rock represents 75% of measured cliff retreat. This fact biased the analysis by mostly documenting erosion distribution in higher values. The weight of this bias can be approached thanks to the French CEREMA study. This study contains null erosion values for coastal sectors where the cliff was not seen to recess in a detectable manner on historical photographs. Yet this detection threshold is deemed to be of the order of 10 $\mathrm{cm.yr^{-1}}$ (Perherin et al., 2012), which is rather high, and null recession could reflect erosion situations anywhere in the spectrum between 0 and 10 $\mathrm{cm.yr^{-1}}$.

These null values represent 67% of the study rocky coasts, which means that low erosion rocky coasts are common and ignoring this information can probably affect conclusions. In order to check the importance of the bias induced by those values, we explored two extreme cases. The erosion value was set to either a small value of 1 $\mathrm{mm.yr^{-1}}$ or to the detection threshold of 10 $\mathrm{cm.yr^{-1}}$. Table 2 shows the influence of the null value in the distribution of erosion rate for the three Hoek and Brown rock strength classes. While the median and quantile absolute values are affected by the value attributed to null observations(TABLE), the expected order of rock sensitivity to erosion is maintained. Weak rocks erode at higher rates than medium and hard rock. Therefore, we trust this result. Further, the dependency relationships flagged earlier remain. A weak positive correlation still exists between frost day frequency and a maximum tidal efficiency for tidal range between 1 and 3 m still is observed.

4.2.4 Cliff retreat vs platform evolution and rock coast erosion

The cliff retreat rates discussed here cannot capture the overall rock coast erosion complexity. In particular, it is obvious that the rock shore platform coevolves with the cliff (e.g. Sunamura, 1992; Moses and Robinson, 2011; de Lange and Moon, 2005). Sunamura (1992) proposes that the shore platform erodes vertically at a rate proportional to its dip and cliff retreat. The processes driving this vertical erosion are numerous (cf. introduction). It has also been proposed that the shore platform width reflects the total cliff retreat since the Holocene transgression and thus the average rock coast erosion since then (cf. Regard et al., 2012). Applied to our findings, these ideas imply that harder rocks leading to slower cliff retreat come with steeper platform slopes.

On the one hand, platform width may be a powerful proxy to long-term cliff retreat. This analysis is not currently possible due to the fact the seaward platform boundary is not obvious (Kennedy, 2015) and to a lack of worldwide information on rock shore platform widths. On the other hand, this idea is debated, because it implicitly favors the static model for the evolution of shore platform instead of the equilibrium model (see de Lange and Moon, 2005; Stephenson, 2008; Moon and de Lange, 2008; Dickson M.E. et

Beyond its width, the rock platform behaviour encompasses the dynamics of scree apron lying on it and possibly shielding it from sea action (cf. Regard et al., 2012). Indeed, cliff collapse is the only stage within platform/cliff erosion cycle leading to apparent retreat. This transitory character could lead to long-term cliff retreat rate under- or overestimation. Working with an important dataset like the one presented here averages data variability, ensuring the extrema are not too much represented (cf. section 4.2.1).

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 and for medium resistance rock types. 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.

5 Conclusions

Compared to ~~inshore~~ continental cliffs, coastal cliffs obviously erode quicker because of the sea presence. The GlobR2C2 v1.0 database compiles ca. 2000 ~~rocky coast~~ coastal rocky cliff retreat data from an online global literature search published before 2016. It is the first attempt of this kind since Sunamura's seminal publication in 1992. The investigated period adds information arising from the quantitative revolution of lidar technology, structure-from-motion technique, accessible to scientists with little background in photogrammetry and massive release of aerial photographic archives of mapping agencies from western countries. The data compiled in GlobR2C2 is heterogeneously distributed in terms of retreat rates, geographical location, cliff nature and climate settings. Even if further research should aim at completing little studied geomorphic contexts of the globe, existing information clearly shows that cliff retreat is most clearly governed by the lithological nature of the cliffs. The dependence of cliff recession rates on rock types is best expressed using a geotechnical parameter, the Hoek and Brown (1997) macroscopic rock mass strength parameter. Rocks classed as weak (recession rate median: 23 $\mathrm{cm.yr^{-1}}$) erodes 2-3 times faster than medium strength rocks (median rate: 10 $\mathrm{cm.yr^{-1}}$), themselves erode 2-3 times faster than hard rocks (median rate: 2.9 $\mathrm{cm.yr^{-1}}$). Using solely a lithology denomination in the way of Woodroffe (2002) historical graph (Fig.~~9~~10), lithologic types exhibit a similarly ordered behaviour (Fig.6), even if geologists contest the robustness of these denominations as proxies for rock strength.

Together with cliff settings compiled from publications, GlobR2C2 also records continental climate and marine conditions at study sites from reanalysed models for their global, spatial and temporal sampling regularity. Both forcings exhibit weak relations with cliff recession rates. In relative terms, however, climate (i.e. frost days frequency) exhibits a stronger influence than marine forcing. Influence of the sea is only slightly visible in this dataset through a maximum efficiency of erosion for tidal ranges between 1 and 3 meters.

Our data divides into three classes of resistance, following the Hoek and Brown parameter. The most resisting (respectively least resisting) rocks are found to lead to retreat rates less than ~~0.1 (Q83~~10 $\mathrm{cm.yr^{-1}}$ (83% quantile) (respectively up to 85~~cm~~ $\mathrm{cm.yr^{-1}}$). Medium-resistance rocks are not studied enough to give a precise range of retreat rates. Climate seems to be more efficient and frost seems to have the strongest influence.

We conclude at this stage that ~~rocky coast~~ coastal rocky cliff erosion is primarily driven by cliff settings with second-order but non-negligible modulations by marine and continental forcings (Fig.2). These findings are of primary interest for coastal erosion models which, up to now, focus mostly on marine forcing ~~(e.g., Anderson et al., 1999; Trenhaile, 2000)~~(e.g. Anderson et al., 1999; Tre

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5.1

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Figure 1. Evidence of sea driving coastal cliff erosion. The cliff in to the foreground is similar ~~than~~ to that in the background except that the one in the background has been protected from the sea by a sand spit. Obviously, the cliff with sea at its base retreats faster (the cliff face is more or less vertical). Photo from Punta Quilla, Patagonia, Argentina.

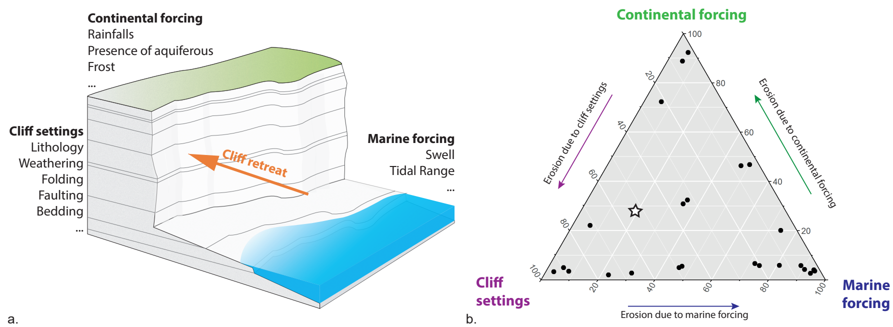


Figure 2. a. Scheme Sketch diagram of rocky cliff erosion drivers. b. Relative cliff retreat drivers reported from published litteratureliterature in GlobR2C2. Eroding factors Factors of influence are are grouped within three main classes: (i) "marine forcing", (ii) "continental forcing" encompassing weather condition conditions and continental groundwater, and (iii) "cliff settings". Authors point of view Responsible forcings cited by authors in publication's abstract is summarised as a percentage of those three forcing based on abstract content. The star positions anticipates our position given the result of results emerging from the present studyGlobR2C2 data base.

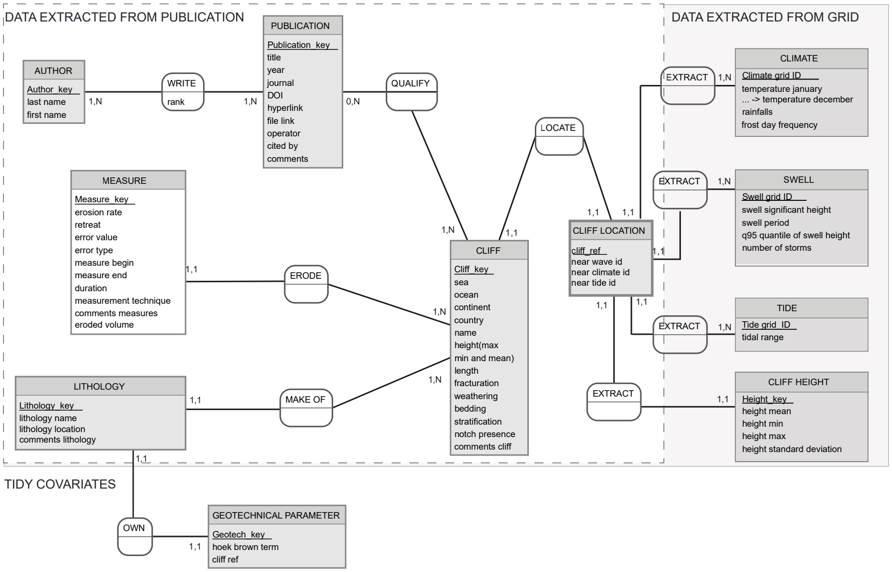


Figure 3. Conceptual data model of cliff erosion database ~~globr2c2~~GlobR2C2. Primary ~~key~~ keys are underlined and numbers are cardinalities.

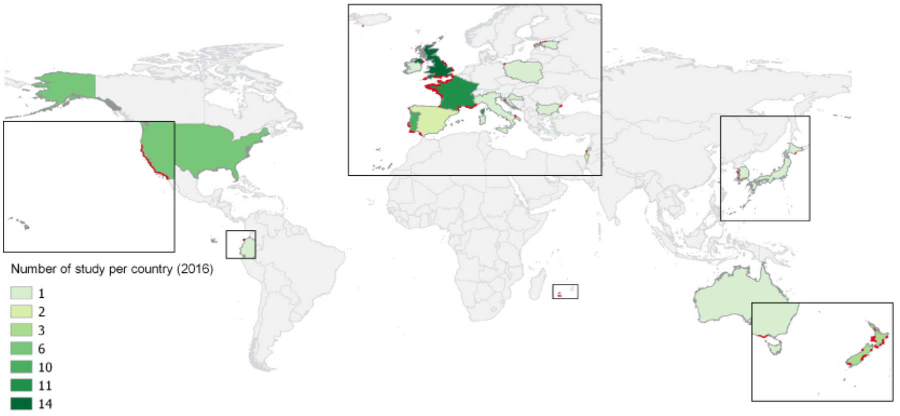


Figure 4. Cliff site locations (red dots) and number of studies by country contained in the database GlobR2C2 (~~publication~~ published before 2016)

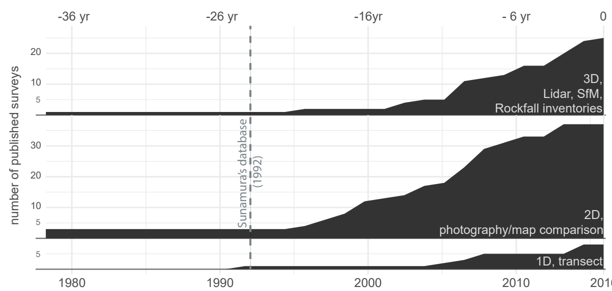


Figure 5. ~~Number~~ Time line of ~~rocky cost~~ cliff erosion ~~studies per different~~ publications recorded in GlobR2C2 differenciated by measurement method~~trough time~~.

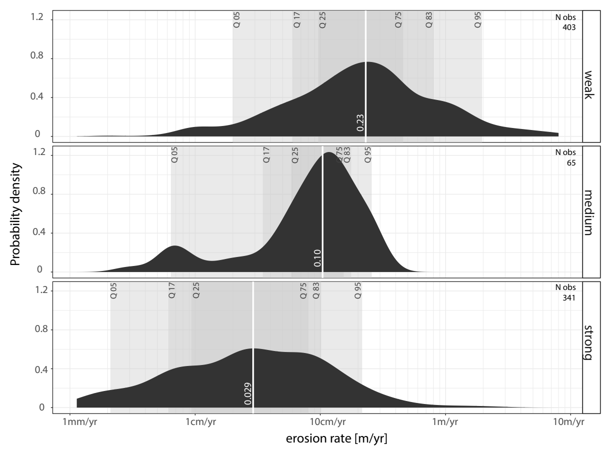


Figure 6. ~~Erosion rate distribution for each one of the rock resistance class. Those resistance classes were attributed according to a simplified hoek~~ Cliff recession rates differenciated using Hoek and ~~brown~~ Bown rock mass strength criterion~~merging~~ , which merges lithological ~~description~~ descriptions and fracturing/weathering state of the cliff rock.

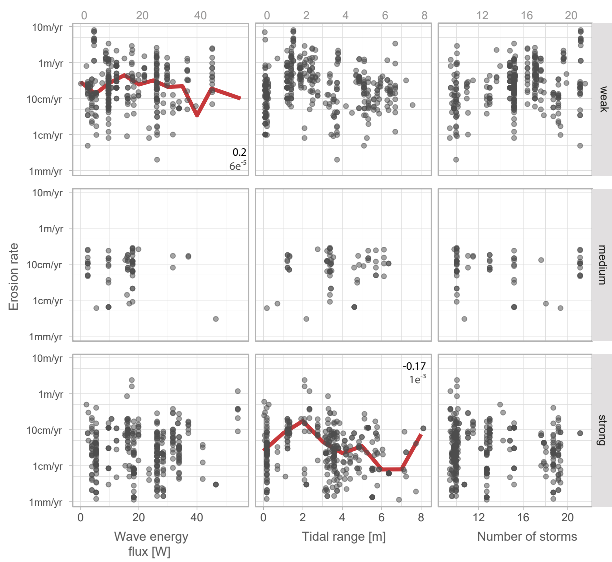


Figure 7. Erosion rate ~~vs~~ versus marine forcings (wave energy flux [~~w~~W], tidal range [m] and number of storms) for each one of the ~~hoek-brown~~ Hoek-Brown rock resistance class. Lines beneath scatterplots represents moving median per bin and numbers are Spearman's correlation coefficient. They were only repesented when p-value was significant.

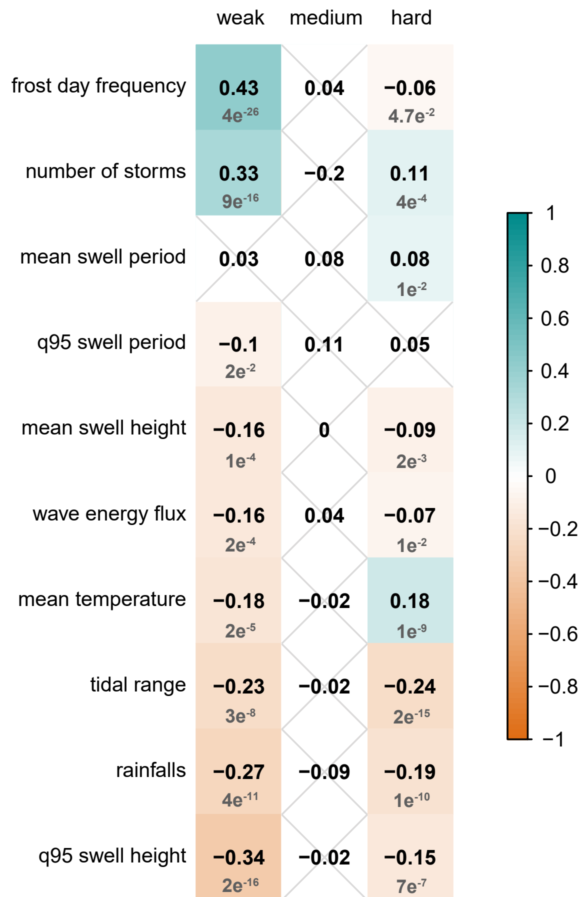


Figure 8. Spearman's rank correlation matrix between forcing and erosion rate for the three type of rock resistance. Values in black are Spearman's correlation coefficient. Grey values are associated p-value when significant (< 0.05)

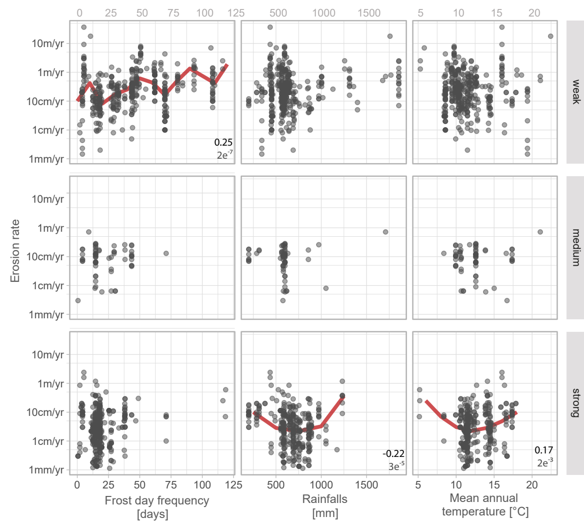


Figure 9. Erosion rate ~~vs~~ versus climate forcings (frost day frequency [days], annual cumulated rainfalls [mm] mean annual temperature [~~]C)~~ °C] for each one of the ~~hoek-brown~~ Hoek-Brown rock resistance class. ~~Lines beneath~~ Overprinted lines on scatterplots ~~represents~~ represent moving median ~~per bin~~ and numbers are Spearman's rank correlation coefficient. They were only ~~repesented~~ represented when p-value was significant (>$2e^{-2}$)

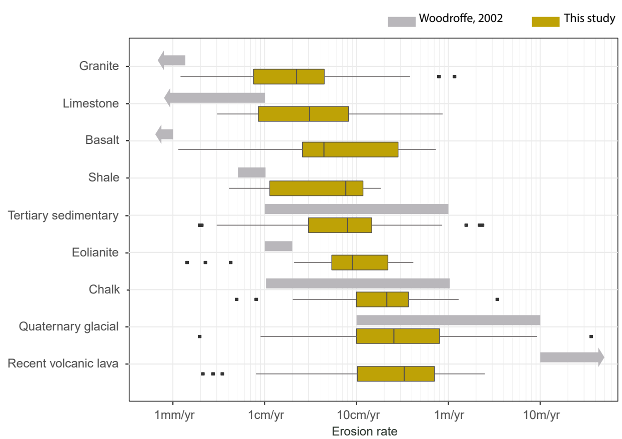
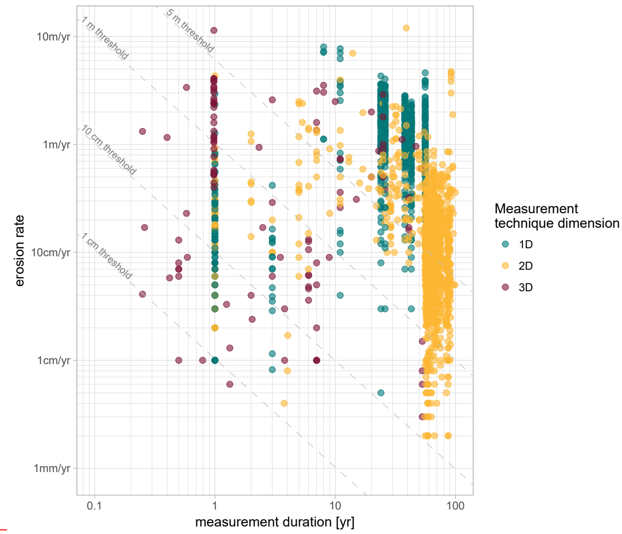


Figure 10. ~~Range~~ Ranges of erosion rate within different lithology. Comparison between ~~woodroffe~~Woodroffe's 2002 study and this one.



~~Survey time vs erosion rate by groups of measuremant techniques.~~

Figure 11. Survey time versus erosion rate by groups of measurement techniques.

Table 1. Field estimates of uniaxial compressive strength (Hoek and Brown, 1997) associated with Hoek and Brown term in the database and corresponding lithologies in the database.

Hoek and Brown table						Recorded in GlobR2C2 as	
Grade	Term	Uniaxial Comp. Strength (Mpa)	Point Load Index (Mpa)	Field estimate of strength	Examples	Hoek and Brown term	Unique lithologic name instances
R6	Extremely strong	> 250	> 10	Specimen can only be chipped with a geological hammer	Fresh basalt, chert, diabase, gneiss, granite, quartzite	hard	basalt, conglomerate, flysh, gneiss, granite, greywacke, intermediate rocks, lavas (basalts, etc), limestone, marly limestone, metamorphic, mudstone, plutonic, sandstone, schist, shale, siltstone, volcanic rock, volcano-sedimentary
R5	Very strong	100 -250	4 - 10	Specimen requires many blows of a geological hammer to fracture it	Amphibolite, sandstone, basalt, gabbro, gneiss, granodiorite, limestone,marble, rhyolite, tuff		
R4	Strong	50 - 100	2 - 4	Specimen requires more than one blow of a geological hammer to fracture it	Limestone, marble, phyllite, sandstone, schist, shale		
R3	Medium strong	25 - 50	1 - 2	Cannot be scrapped or peeled with a pocket knife, specimen can be fractured with a single blow from a geological hammer	Claystone, coal, concrete, schist, shale, siltstone	medium	claystone, shale, slate, volcanic tuff, sandstone, shale, limestone, marl, siltstone, basalt, marl and consolidated clay
R2	Weak	5 - 25	†	Can be peeled with a pocket knife with difficulty, shallow indentation made by firm blow whith point of a geological hammer	Chalk, rocksalt, potash	weak	aeolianite, argilites, basalt, chalk, clay, conglomerate, dune deposits, fluvial deposits, glacial deposits, glaciofluvial, gravels, head, lahar deposits, loess and silts, marl, sand, sand , sandstone, scories, silt, till, tuff, undifferentiated recent
R1	Very weak	1 - 5	†	Crumbles under firm blows with point of a geological hammer, can be peeled by a pocket	Highly weathered or altered rock		

Table 2. Influence Distribution characteristics of cliff erosion rates (in m.yr-1) compiled from publications in GlobR2C2 differenciated by Hoek and Brown rock resistence types. The table's different lines reflect how characteristic distribution values change by changing the erosion rate value assignation for CEREMA estimates under affected to cliffs instances where erosion rates were smaller than the detection threshold in the CEREMA study (0.1) on erosion distribution n instances for N total observations). Null values were handled in three different strength classesways: (i) insignificant rates removed from distribution computation; (ii) Null values are used and assigned an arbitrary low erosion rate of 0.001 m.yr-1; (iii) Null values are used and assigned an arbitrary rate of 0.1 m.yr-1.

	weak rock cliffs					medium rock cliffs				
	med Q5	q5 Q17	q27 Q50	q83 Q83	q95 Q95	med Q5	q5 Q17	q27 Q50	q83 Q83	q95
without null null removed	0.23 0.018	0.1	0.23	0.85	2.499	0.104 0.006	0.063	0.104	0.18	0.
null = 0.01 0.001	0.129 0.001	0.006	0.129	0.683	1.806	0.102 0.002	0.049	0.102	0.18	0.
null = 0.1	0.129 0.01	0.1	0.129	0.683	1.806	0.102 0.006	0.063	0.102	0.18	0.