1 **A global spatially explicit database of changes in island**
2 **paleo-area and archipelago configuration during the late**
3 **Quaternary**

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34
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ABSTRACT

Motivation: Past sea level fluctuations have shaped island area and archipelago configuration. The availability of global high resolution data on bathymetry and past sea levels allows reconstruction of island paleogeography. Studies on the role of paleo-area often only consider the last glacial maximum, which neglects the dynamics of island fusion and fission resulting from cyclic sea level fluctuations over the Quaternary. Currently, no global database is available to test the role of changing island geographies driven by Quaternary sea level change on evolutionary, ecological, and archaeological patterns. However, data on island paleo environments is crucial for understanding insular biodiversity distributions and human settlement patterns. Here, we present the Paleo Islands and Archipelago Configuration (PIAC) database, containing sea level driven paleogeography changes over the late Quaternary of 178 islands in 27 archipelagos, and discuss its relevance, limitations and uncertainties. The R functions developed to create the PIAC database are provided to allow calculations for other islands, time steps, sea-level curves, and higher spatiotemporal resolutions.

Main types of variable contained: Polygon shapefiles with archipelago configuration and tables with paleo-area per island.

Spatial location and grain: The database has a global representation, with 27 archipelagos being covered: Aldabra, Azores, Balearic Islands, California Channel Islands, Canary Islands, Cape Verde, Comoros, Cook Islands, Crozet Islands, Dutch Caribbean, Galápagos, Gulf of Guinea, Hawaii, Inner Seychelles, Juan Fernández, Kuril Islands, Madeira, Marianas, Marquesas, Mascarenes, Phoenix Islands, Pitcairn Islands, Prince Edward Islands, Revillagigedo, Samoan Islands, Society Islands, and Tristan da Cunha. All data are at 1km² spatial resolution.

Time period and grain: The focus of this paper is on the last 35ka; data for the last 140ka are also provided. The grain is 1ka temporal resolution.

Level of measurement: Data are per island, grouped per archipelago.

Software format: The data were produced in the R programming language.

81 **INTRODUCTION**

82 Island geographies are highly dynamic. Island area, spatial location and isolation have
83 changed drastically following geological dynamics and sea level fluctuations. These changes
84 in paleogeography have shaped insular species' distributions, as well as human settlement
85 patterns in the past. Recently developed island biogeographic models like the GDM (General
86 Dynamic Model; Whittaker *et al.*, 2008; see Borregaard *et al.*, 2017 for a review) and the
87 GSM (Glacial Sensitive Model; Fernández-Palacios *et al.*, 2016) incorporate the role of long
88 term changes in island geography in predictions of biodiversity patterns. On timescales of
89 <100ka, geographical changes on most oceanic islands are shaped mainly by sea level
90 fluctuations. These fluctuations involve the repetitive fusion and fission of islands, area
91 contraction and expansion, and changes in the number of stepping stones (reducing inter-
92 island isolation) by the emergence and drowning of seamounts (Fernández-Palacios, 2016).

93
94 Recent findings suggest that island area and connectedness at the Last Glacial Maximum
95 (LGM) influenced patterns of terrestrial endemic species richness on islands (Rijsdijk *et al.*,
96 2014; Weigelt *et al.*, 2016) and that sea level changes influenced the distribution of insular
97 shallow-water marine organisms (Ávila *et al.*, 2009; Pinheiro *et al.*, 2017). In addition, sea
98 level fluctuations might have influenced human population dispersal and could have
99 modified the availability of near-shore natural resources for insular human societies (van
100 Andel, 1989; Patton, 1996; Erlandson & Fitzpatrick, 2006; Fitzpatrick & Keegan, 2007;
101 Montenegro *et al.*, 2016). Reconstructed paleo-shorelines have been used by several authors
102 to understand (pre)historic patterns of human dispersal and settlement (Kirch, 2007; Bailey
103 & King, 2011; Lambeck *et al.*, 2011; Ferentinos *et al.*, 2012). Therefore, data on the dynamics
104 of island paleo environments and geographies might help to resolve key questions in island
105 biogeography (Patiño *et al.*, 2017) and island archaeology (Erlandson & Fitzpatrick, 2006;
106 Montenegro *et al.*, 2016).

107
108 Until now, temporal dynamics of paleogeography – e.g. the duration over which islands were
109 connected, and the rates at which island area changed – remained relatively underexplored.
110 Biogeographic and macroecological studies have so far mainly explored the role of one
111 (static) sea level stand like the current high sea level stand or the extreme low stand at the
112 LGM, while both are highly exceptional when considering the last 1 Ma (van Andel, 1989;
113 Bintanja *et al.*, 2005; Woodruff, 2010). In this paper, we present a global, spatially explicit
114 database with a quantification of changes in island paleo-area and reconstructions of
115 archipelago configuration driven by sea level fluctuations during the late Quaternary. This
116 Paleo Islands and Archipelago Configuration (PIAC) database consists of 178 islands located
117 in 27 archipelagos spread around the globe (see Fig. 1 for an overview). Here, we extend
118 previous work by reconstructing island paleogeography dynamics on a multi-millennial
119 timescale and global coverage. In the subsequent sections we describe the methods by
120 which the data were derived, we provide the technical validation and discuss the reliability of
121 the database as well as possible applications.

122 **METHODS**

123 A method to calculate paleo-area change driven by sea level fluctuations was developed by
124 Rijsdijk *et al.* (2013, 2014). To create the PIAC database we have enhanced the method
125 developed by Rijsdijk *et al.* (2013, 2014): we used higher quality input data, the computation
126 time is reduced, the contouring method has been improved, and the model is applied to a
127 larger number of archipelagos (Fig. 1). The workflow was subdivided into four steps (Fig. 1):
128 collecting input data, intermediate processing, generating output data, and data validation.

129
130 <FIGURE 1>
131

To quantify paleo-area, three types of input data were used: The GEBCO_2014 Grid (www.gebco.net) which is a global 30 arc-second bathymetry Digital Elevation Model (DEM; GEBCO, 2014); a global mean sea level curve from Lambeck *et al.* (2014) spanning 35ka, based on inverse modelling of ~1,000 far field data points and incorporating glacial isostatic adjustment (i.e. the viscoelastic response of the earth-ocean system to glacial cycles); and spatial coordinates corresponding to island centre points per archipelago. Even though sea level curves exist that span longer timescales (e.g. Cutler *et al.*, 2003; Bintanja *et al.*, 2005), we used the curve from Lambeck *et al.* (2014) because (1) to our knowledge, it is the most recently developed global mean sea level curve, (2) it is focused particularly on far-field locations (the vast majority of archipelagos in the data are distant from major ice-sheets), and (3) the proportional contribution of geological processes to area change and the uncertainty of sea level reconstructions increases for longer timescales (e.g. Price *et al.*, 2002; Miller *et al.*, 2008; Lambeck *et al.*, 2014). Even though we focussed on reconstructions for a time span of 35ka, as an illustration of the method, data for 140ka based on Cutler *et al.* (2003) are also provided. The sea level curve was used to delimit polygons where the bathymetry DEM was above sea level at each time step. All islands that were above sea level (including presently submerged seamounts) were stored in separate polygon shapefiles per 1ka time step. The coordinates of island centre points were used to identify islands according to their current names and to store their paleo-area at each time step in a table. To assess the quality of the calculated island area, we compared the area calculated from the bathymetry DEM at the present-day sea level (0ka) to the current area from the global database of administrative areas (GADM, www.gadm.org) as reported in a dataset on present-day environmental characteristics of marine islands worldwide (Weigelt *et al.*, 2013). For a few islands missing from that dataset, current area was obtained from other sources. Four island pairs could not be separated at the 30 arc-second resolution and their area was hence summed in the validation data. The reconstruction of archipelago configuration and paleo-area was carried out in R (R Core Team, 2016) version 3.3.2.

159 RESULTS

160 Description of the database

Paleo-area and archipelago configurations were reconstructed for 178 islands within 27 archipelagos. The PIAC database is stored for a time span of 35ka (Lambeck *et al.*, 2014) and 140ka (Cutler *et al.*, 2003). The workflow for producing the PIAC database (R scripts and associated files) is organized within separate folders for each processing step (Fig. 1): input, intermediate, output. The PIAC database and the workflow (Table 1) can be downloaded separately from ISLANDLAB (<http://islandlab.uac.pt/software/ver.php?id=28>) and PANGAEA (<https://doi.pangaea.de/10.1594/PANGAEA.880585>).

169 <TABLE 1>

171 In Fig. 2 the data on archipelago configuration and paleo-area are visualized for the Canary Islands. Because of bathymetric differences, each island shows a unique area change signature. Similar graphs of paleo-area change for other archipelagos are presented in Appendix S2 for a time span of 35ka (Lambeck *et al.*, 2014) and 140ka (Cutler *et al.*, 2003).

176 <FIGURE 2>

178 Validation

179 The comparison of the area calculated at the present-day sea level with the actual current island area indicates that they are highly correlated (Pearson product-moment correlation coefficient, $r = 0.99$; Appendix S3). For most islands, the calculated area is slightly larger than the actual area, while in a few cases it is smaller. The deviations stem from the spatial

183 resolution (30 arc-second) of the bathymetry DEM. Consequently, the proportional
184 deviations are larger for small islands (Appendix S3).

185 **DISCUSSION**

186 **Accuracy**

187 Possible inaccuracies in the calculated paleo-area and reconstructed archipelago
188 configuration stem from two factors: i) the resolution of the bathymetry DEM (30 arc-
189 second; roughly 1 km at sea level at the equator). To our knowledge, there is no publicly
190 available global bathymetry DEM with a higher resolution than the one used to produce this
191 database. As DEMs with higher resolution become available, the code accompanying this
192 paper can be applied to generate outputs with increased accuracy; ii) we used a global mean
193 sea level curve for reconstructing regional geographies. Sea level is not uniform across the
194 globe, regional deviations are caused by the complex interactions between oceans, ice-
195 sheets, and the Earth's crust, including geological processes (e.g. glacial isostatic adjustment,
196 and vertical land movement resulting from both gradual and sudden tectonic processes),
197 variations in ocean mass and density, and 'fingerprint' effects such as the gravitational
198 attraction between water and ice-sheets (Farrell & Clark, 1976; Clark *et al.*, 1978; Milne &
199 Mitrovica, 2008; Raymo *et al.*, 2011; Lambeck *et al.*, 2014; Kopp *et al.*, 2015). Although these
200 different processes might negate each other, regional deviations from the global sea level
201 curve of several meters are possible (Milne & Mitrovica, 2008; Woodroffe *et al.*, 2012; Kopp
202 *et al.*, 2015). Since the sea level curve from Lambeck *et al.* (2014) was developed for far-field
203 regions (regions far from former ice-sheets), our reconstructions of paleo-area and
204 archipelago configuration for islands located in – or close to – tropical regions are likely have
205 the highest accuracy. Whether or not the inaccuracies stemming from the above outlined
206 factors are relevant for specific archipelagos should be decided based on the spatiotemporal
207 scale and scope of the project. While some studies have reconstructed changing island
208 geographies resulting from both geological processes and sea level fluctuations for specific
209 archipelagos over timescales of several 100ka (e.g. Price & Elliott-Fisk, 2004; Ali & Aitchison,
210 2014), making such detailed reconstructions over long timescales is currently unfeasible for
211 many archipelagos due to lack of data, and is therefore currently impossible on a global
212 scale.

213 **Applications**

214 The global PIAC database enables moving beyond a focus on extreme archipelago
215 configurations, such as during the present interglacial high or the LGM (see Voris, 2000;
216 Warren *et al.*, 2010; Ferentinos *et al.*, 2012 for examples using multiple time steps). The
217 database permits assessment of the potential for vicariance events and stepping stone
218 dispersal in evolutionary and biogeographical studies (see Fordham *et al.* (2017), who
219 provide a similar line of argumentation for paleo climate). For instance, the database might
220 facilitate answering questions such as: what is the influence of repetitive fusion and fission of
221 paleo islands (such as Mahan into Fuerteventura and Lanzarote; Fig. 2) on biodiversity and
222 phylogenetic patterns? And, is present-day beta diversity related to inter-island paleo-
223 distance? The database also allows for the reconstruction of coastal environments for
224 archaeological studies, exploration of potential archaeological sites in currently submerged
225 regions (Lambeck & Chappell, 2001; Erlandson & Fitzpatrick, 2006; Rick *et al.*, 2013), and the
226 development of simulation models in human dispersal studies (Ferentinos *et al.*, 2012;
227 Montenegro *et al.*, 2016).

228 Area or isolation metrics derived from the PIAC database can be used as explanatory
229 variables in macroecological and evolutionary studies. Examples of metrics that could be
230 calculated from the database are: rate of area change; minimum, maximum, or average area
231 over a biogeographically relevant time period; or the mean, minimum and maximum inter-
232 island distance. For local scale biogeographic, phylogenetic, population genetic, and

archaeological studies, we recommend use of a regional sea level curve where available (van Andel, 1989; Warren *et al.*, 2010; Simaïakis *et al.*, 2017). In addition, regional crustal tectonic or other effects leading to temporal deviations from the global mean curve are not incorporated. In cases when precise timings of geographic change are required, reference to known local deviations from the global mean sea level curve is recommended. The database presented in this paper should be regarded as an approximation of paleo-area and archipelago configuration shaped by sea level fluctuations to be refined as new data and methods become available. The R scripts and functions included in the database allow more detailed calculations for specific islands or archipelagos where a regional sea level curve or a high-resolution bathymetry DEM exists.

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SUPPORTING INFORMATION

Appendix S1 Percentage of time sea level was below certain level during last 1 Ma.

Appendix S2 Paleo-area change (35ka and 140ka).

Appendix S3 Accuracy and validation.

DATA ACCESSIBILITY STATEMENT

The PIAC database and the R scripts are shared at ISLANDLAB (<http://islandlab.uac.pt/software/ver.php?id=28>) and PANGAEA (<https://doi.pangaea.de/10.1594/PANGAEA.880585>), under the CC BY 4.0 license (<https://creativecommons.org/licenses/by/4.0/>).

BIOSKETCH

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Author contributions: All authors contributed ideas; S.J.N., J.B.B., T.H., and E.E.v.L. developed the methodology; S.J.N. led the writing, with input from all co-authors.

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391
392

393 **TABLES**

394
395 **Table 1** Overview and description of files related to the Paleo Islands and Archipelago Configuration (PIAC)
396 database and workflow. The PIAC database ^(DB) is available for 1ka time steps over a period of 35ka and 140ka
397 (created data are in the World Sinusoidal projection, EPSG code: 54008). For each of the files contained in the
398 PIAC database ^(DB) and workflow ^(WF), the processing step (IN, INTER, OUT) is indicated and a file description is
399 provided.

File name, processing step, (database/workflow)	File format	Description (and source)
archipelago_shp _{OUT} ^(DB)	Folder with ESRI polygon shapefiles (.shp)	Archipelago configuration and island shorelines with polygons for each present-day island that was above sea level for each 1ka time step
area_archipelago _{OUT} ^(DB)	CSV and XLSX	Paleo-area (km ²) for each 1ka time step for islands within an archipelago
area_global _{OUT} ^(DB)	CSV and XLSX	Paleo-area (km ²) for each 1ka time step for all islands in the database
archipelagoDEMsin _{INTER} ^(WF)	GeoTIFF (.tif)	Bathymetry Digital Elevation Model (DEM) for each archipelago
archipelago_pnt _{IN} ^(WF)	KML	Centre points of islands within an archipelago
GEBCO_2014_1D _{IN} ^(WF)	netCDF	Global Digital Elevation Model (including bathymetry) from GEBCO (2014). The file can be downloaded from https://www.gebco.net/data_and_products/gridded_bathymetry_data/
time_level_Lambeck _{IN} ^(WF) time_level_Cutler _{IN} ^(WF)	Serialized R object (.rds)	Global mean sea level curves (meters relative to present sea level) from Lambeck <i>et al.</i> (2014) and Cutler <i>et al.</i> (2003)
PIAC_run ^(WF)	R script	Workflow for preparing the data
PIAC_functions ^(WF)	R script	Functions for preparing the data

400
401

FIGURES

Figure 1 The top panel provides an overview of archipelagos in the PIAC database. 1. Aldabra; 2. Azores; 3. Balearic Islands; 4. California Channel Islands; 5. Canary Islands; 6. Cape Verde; 7. Comoros; 8. Cook Islands; 9. Crozet Islands; 10. Dutch Caribbean; 11. Galápagos; 12. Gulf of Guinea (São Tomé and Príncipe, Annobón); 13. Hawaii; 14. Inner Seychelles; 15. Juan Fernández; 16. Kuril Islands; 17. Madeira; 18. Marianas; 19. Marquesas; 20. Mascarenes; 21. Phoenix Islands; 22. Pitcairn Islands; 23. Prince Edward Islands; 24. Revillagigedo; 25. Samoan Islands (Samoa and American Samoa); 26. Society Islands; 27. Tristan da Cunha. The lower panel shows the outline of the experimental workflow used to generate the Paleo Islands and Archipelago Configuration (PIAC) database. The processing steps are carried out separately for each archipelago. A global Bathymetry Digital Elevation Model and a global sea level curve are used as input data. Per 1ka time step, locations where the land is above sea level are delineated as polygons. The island centre points are used to identify the islands for which paleo-area is calculated. The calculated area for the present sea level are compared to the current area by calculating the Pearson product-moment correlation coefficient (r).

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420 **Figure 2** Changes in paleo-area within the Canary Islands. The map on the left shows the archipelago
421 configuration at 20ka (dark grey), with the present archipelago configuration added as a reference (light grey).
422 The right panel shows the reconstructed paleo-area changes (km²) for the seven major islands of this archipelago
423 over a period of 35ka. The figure was created by using the sea level curve from Lambeck et al. (2014).

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BLACK AND WHITE FIGURES

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447

Appendix S1: Percentage of time sea level was below certain level during last 1 Ma

Figure S1 The percentage of time that the sea level was below a certain sea level during the last 1Ma (figure is based on data from Bintanja *et al.* (2005). 0 meters refers to the present sea level.

References

Bintanja, R., van de Wal, R.S.W. & Oerlemans, J. (2005) Modelled atmospheric temperatures and global sea levels over the past million years. *Nature*, **437**, 125–8.

Appendix S2: Paleo-area change (35ka and 140ka)

Changes in paleo-area over a period of 35ka and 140ka for a selection of seven archipelagos. The graphs were created by using respectively the sea level curve from Lambeck *et al.* (2014) and Cutler *et al.* (2003). The X-axis represents the time in ka before present; the Y-axis reflects the area of each island in km².

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- Lambeck, K., Rouby, H., Purcell, A., Sun, Y. & Sambridge, M. (2014) Sea level and global ice volumes from the Last Glacial Maximum to the Holocene. *Proceedings of the National Academy of Sciences of the United States of America*, **111**, 15296–303.

Appendix S3: Accuracy and validation

Figure S1 Relationship between current island area as calculated from the bathymetry Digital Elevation Model (DEM) by using the present-day sea level (0ka) and current area from www.gadm.org as reported in Weigelt *et al.* (2013).

Figure S2 The proportional difference between calculated and reported area is larger for small islands (left) than for large islands (right). The area calculated from the bathymetry Digital Elevation Model (DEM) by using the present-day (0ka) sea level (dark grey grid cells) and reported area (light grey, semi-opaque polygons). Shown are two examples from the Azores (left: Corvo, right: Terceira).

Figure S3 Orona (Phoenix archipelago), a low-lying atoll for which area is highly underestimated. The atoll is just a few meters above sea level (light grey, semi-opaque polygons). At the 30 arc-second resolution of the bathymetry Digital Elevation Model (DEM), only a single grid cell is above sea level (dark grey grid cells).

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Title:

A global spatially explicit database of changes in island palaeo-area and archipelago configuration during the late Quaternary

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