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

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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 palaeo-geography. Studies on the role of palaeo-area often consider only the Last Glacial Maximum, which neglects the dynamics of island fusion and fission resulting from cyclic sea level fluctuations throughout 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 palaeo-environments is crucial for understanding insular biodiversity distributions and human settlement patterns. Here, we present the Palaeo-Islands and Archipelago Configuration (PIAC) database, containing sea level-driven palaeo-geography 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 spatio-temporal resolutions.

Main types of variables contained: Polygon shapefiles with archipelago configuration and tables with palaeo-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 1 km² spatial resolution.

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

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

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

KEYWORDS

general dynamic model, glacial sensitive model, insular biodiversity patterns, island archaeology, island biogeography, Pleistocene climate change, palaeo-geography, palaeo-shorelines, prehistoric human settlement patterns, sea level fluctuations

1 | INTRODUCTION

Island geographies are highly dynamic. Island area, spatial location and isolation have changed drastically following geological dynamics and

sea level fluctuations. These changes in palaeo-geography have shaped insular species' distributions, as well as human settlement patterns in the past. Recently developed island biogeographical models, such as the general dynamic model (GDM; Whittaker, Triantis, & Ladle, 2008;

see Borregaard et al., 2017 for a review) and the glacial sensitive model (GSM; Fernández-Palacios et al., 2016) incorporate the role of long-term changes in island geography in predictions of biodiversity patterns. On time-scales of < 100 kyr, geographical changes on most oceanic islands are shaped mainly by sea level fluctuations. These fluctuations involve the repetitive fusion and fission of islands, area contraction and expansion, and changes in the number of stepping stones (reducing inter-island isolation) by the emergence and drowning of seamounts (Fernández-Palacios, 2016).

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

Until now, temporal dynamics of palaeo-geography (e.g., the duration over which islands were connected and the rates at which island area changed) remained relatively underexplored. Biogeographical and macroecological studies so far have mainly explored the role of one (static) sea level stand, such as the current high sea level stand or the extreme low stand at the LGM, although both are highly exceptional when considering the last 1 Myr (Supporting Information Appendix S1; Bintanja, van de Wal, & Oerlemans, 2005; van Andel, 1989; Woodruff, 2010). In this paper, we present a global, spatially explicit database with a quantification of changes in island palaeo-area and reconstructions of archipelago configuration driven by sea level fluctuations during the late Quaternary. This Palaeo-Islands and Archipelago Configuration (PIAC) database consists of 178 islands located in 27 archipelagos spread around the globe (see Figure 1 for an overview). Here, we extend previous work by reconstructing island palaeo-geography dynamics on a multi-millennial time-scale and with global coverage. In the subsequent sections, we describe the methods by which the data were derived, we provide the technical validation and discuss the reliability of the database and possible applications.

2 | METHODS

A method to calculate palaeo-area change driven by sea level fluctuations was developed by Rijsdijk, Hengl, Norder, Ávila, & Fernández-Palacios (2013) and Rijsdijk et al. (2014). To create the PIAC database, we have enhanced the method developed by Rijsdijk et al. (2013,

2014); we used higher-quality input data, the computation time is reduced, the contouring method has been improved, and the model is applied to a larger number of archipelagos (Figure 1). The workflow was subdivided into the following four steps (Figure 1): collecting input data, intermediate processing, generating output data, and data validation.

To quantify palaeo-area, three types of input data were used: The GEBCO_2014 Grid (version 20150318; 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, Rouby, Purcell, Sun, and Sambridge (2014) spanning 35 kyr, based on inverse modelling of c. 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 time-scales (e.g., Bintanja et al., 2005; Cutler et al., 2003), we used the curve from Lambeck et al. (2014) because: (a) to our knowledge, it is the most recently developed global mean sea level curve; (b) it is focused particularly on far-field locations (the vast majority of archipelagos in the data are distant from major ice-sheets); and (c) the proportional contribution of geological processes to area change and the uncertainty of sea level reconstructions increase for longer time-scales (e.g., Lambeck et al., 2014; Miller et al., 2008; Price, Clague, Bay, Road, & Landing, 2002). Even though we focused on reconstructions for a time span of 35 kyr, as an illustration of the method, data for 140 kyr 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 1 kyr time step. The coordinates of island centre points were used to identify islands according to their current names and to store their palaeo-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 (0 ka) to the current area from the global database of administrative areas (GADM; www.gadm.org/version1) as reported in a dataset on present-day environmental characteristics of marine islands worldwide (Weigelt, Jetz, & Kreft, 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, hence their area was summed in the validation data. The reconstruction of archipelago configuration and palaeo-area was carried out in R version 3.3.2 (R Core Team, 2016).

3 | RESULTS

3.1 | Description of the database

Palaeo-area and archipelago configurations were reconstructed for 178 islands within 27 archipelagos. The PIAC database is stored for a time span of 35 kyr (Lambeck et al., 2014) and 140 kyr (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

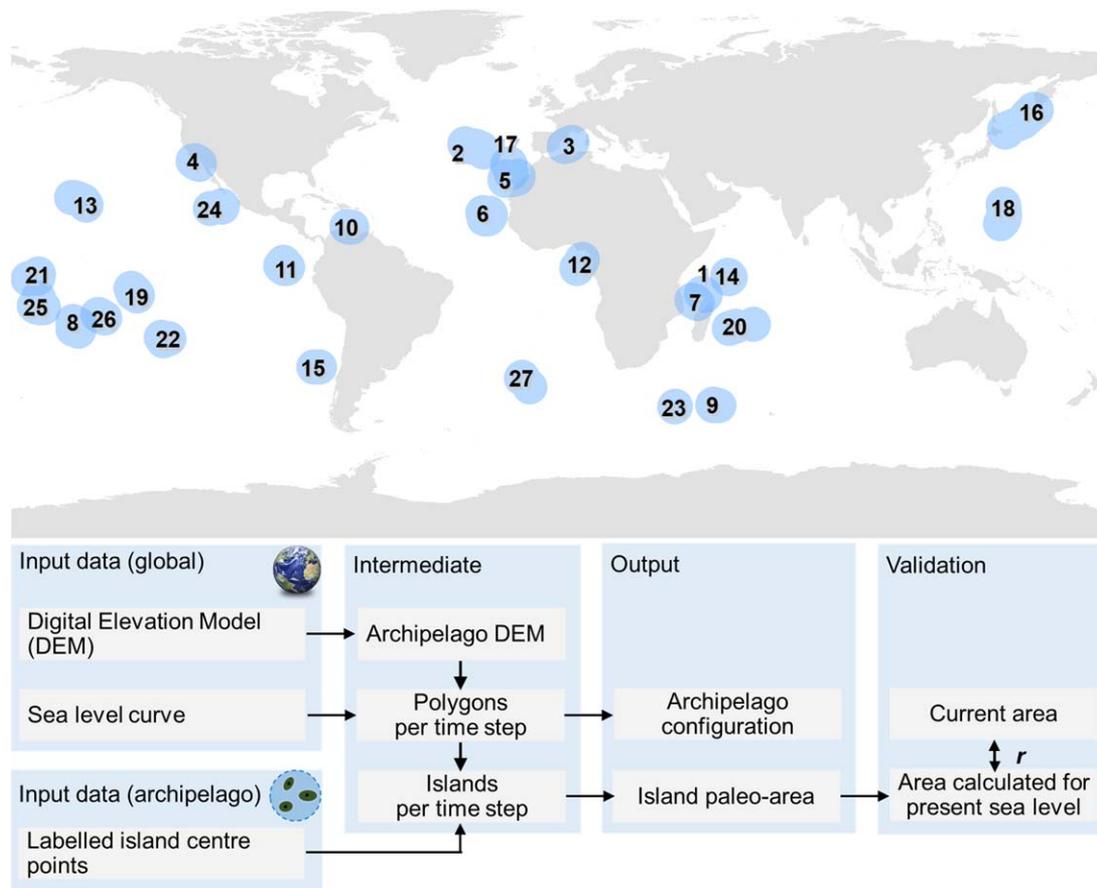


FIGURE 1 The top panel provides an overview of archipelagos in the PIAC database. 1 = Aldabra; 2 = Azores; 3 = Balearic Islands; 4 = California Channel Islands; 5 = Canary Islands; 6 = Cape Verde; 7 = Comoros; 8 = Cook Islands; 9 = Crozet Islands; 10 = Dutch Caribbean; 11 = Galápagos; 12 = Gulf of Guinea (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 Palaeo 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 1 kyr 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 palaeo-area is calculated. The calculated area for the present sea level are compared with the current area by calculating the Pearson product-moment correlation coefficient (r)

(Figure 1): input, intermediate and 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>).

In Figure 2, the data on archipelago configuration and palaeo-area are visualized for the Canary Islands. As a result of bathymetric differences, each island shows a unique area change signature. Similar graphs of palaeo-area change for other archipelagos are presented in Supporting Information Appendix S2 for a time span of 35 kyr (Lambeck et al., 2014) and 140 kyr (Cutler et al., 2003).

3.2 | Validation

The comparison of the area calculated at the present-day sea level with the real current island area indicates that they are highly correlated (Pearson product-moment correlation coefficient, $r = 0.99$; Supporting Information Appendix S3). For most islands, the calculated

area is slightly larger than the real area, but in a few cases it is smaller. The deviations stem from the spatial resolution (30 arc-second) of the bathymetry DEM. Consequently, the proportional deviations are larger for small islands (Supporting Information Appendix S3).

4 | DISCUSSION

4.1 | Accuracy

Possible inaccuracies in the calculated palaeo-area and reconstructed archipelago configuration stem from two factors. The first factor is the resolution of the bathymetry DEM (30 arc-second; c. 1 km at sea level at the equator). To our knowledge, there is no publicly available global bathymetry DEM with a higher resolution than the one used to produce this database. As DEMs with higher resolution become available, the code accompanying this paper can be applied to generate outputs with increased accuracy. Second, we used a global mean sea level curve

TABLE 1 Overview and description of files related to the Palaeo Islands and Archipelago Configuration (PIAC) database and workflow

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 1 kyr time step
area_archipelago _{OUT} ^(DB)	CSV and XLSX	Palaeo-area (km ²) for each 1 kyr time step for islands within an archipelago
area_global _{OUT} ^(DB)	CSV and XLSX	Palaeo-area (km ²) for each 1 kyr 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 the GEBCO_2014 Grid, version 20150318, www.gebco.net. 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 (metres relative to present sea level) from Lambeck et al. (2014) and Cutler et al. (2003)
PIAC_run ^(WF)	R script	Workflow for preparing the data
PIAC_functions ^(WF)	R script	Functions for preparing the data

Note. The PIAC database ^(DB) is available for 1 kyr time steps over periods of 35 and 140 kyr (created data are in the World Sinusoidal projection, EPSG code: 54008). For each of the files contained in the PIAC database ^(DB) and workflow ^(WF), the processing step (_{IN}, _{INTER} or _{OUT}) is indicated and a file description provided.

for reconstructing regional geographies. Sea level is not uniform across the globe; regional deviations are caused by the complex interactions between oceans, ice-sheets and the Earth's crust, including geological processes (e.g., glacial isostatic adjustment, and vertical land movement resulting from both gradual and sudden tectonic processes), variations in ocean mass and density, and 'fingerprint' effects, such as the gravitational attraction between water and ice-sheets (Clark, Farrell, & Peltier, 1978; Farrell & Clark, 1976; Kopp, Hay, Little, & Mitrovia, 2015; Lambeck et al., 2014; Milne & Mitrovia, 2008; Raymo, Mitrovia, Leary, Deconto, & Hearty, 2011). Although these different processes might negate each other, regional deviations from the global sea level curve up to tens of metres are possible (Kopp et al., 2015; Milne &

Mitrovia, 2008; Woodroffe, McGregor, Lambeck, Smithers, & Fink, 2012). Given that the sea level curve from Lambeck et al. (2014) was developed for far-field regions (regions far from former ice-sheets), our reconstructions of palaeo-area and archipelago configuration for islands located in or close to tropical regions are likely to have the highest accuracy. Whether or not the inaccuracies stemming from the factors outlined above are relevant for specific archipelagos should be decided based on the spatio-temporal scale and scope of the project. Although some studies have reconstructed changing island geographies resulting from both geological processes and sea level fluctuations for specific archipelagos over time-scales of several 100 kyr (e.g., Ali & Aitchison, 2014; Price & Elliott-Fisk, 2004), making such detailed reconstructions

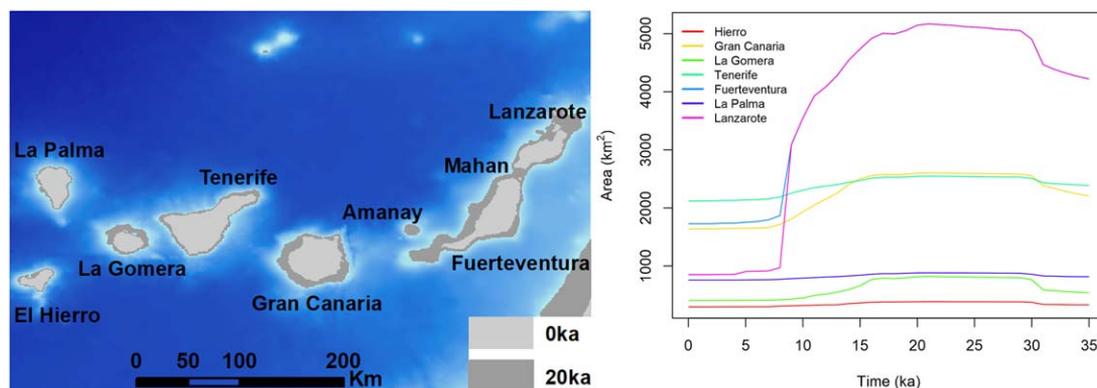


FIGURE 2 Changes in palaeo-area within the Canary Islands. The map on the left shows the archipelago configuration at 20 ka (dark grey), with the present archipelago configuration added as a reference (light grey). The right panel shows the reconstructed palaeo-area changes (in square kilometres) for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

over long time-scales is currently unfeasible for many archipelagos owing to lack of data, and is therefore currently impossible on a global scale.

4.2 | Applications

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

Area or isolation metrics derived from the PIAC database can be used as explanatory variables in macroecological and evolutionary studies. Examples of metrics that could be calculated from the database are as follows: rate of area change; minimal, maximal or average area over a biogeographically relevant time period; or the mean, minimal and maximal inter-island distance. For local scale biogeographical, phylogenetic, population genetic and archaeological studies, we recommend use of a regional sea level curve where available (Simaiakis et al., 2017; van Andel, 1989; Warren et al., 2010). In addition, regional crustal tectonic or other effects leading to temporal deviations from the global mean curve are not incorporated. If precise timings of geographical 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 palaeo-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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All authors contributed ideas; S.J.N., J.B.B., T.H. and E.E.v.L. developed the methodology; and S.J.N. led the writing, with input from all co-authors.

DATA ACCESSIBILITY

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/>).

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BIOSKETCH

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SUPPORTING INFORMATION

Additional Supporting Information may be found online in the supporting information tab for this article.

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