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Palaeo sea-level and ice-sheet databases: problems, strategies and perspectives

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Abstract. Sea-level and ice-sheet databases have driven numerous advances in understanding the Earth system. We describe the challenges and offer best strategies that can be adopted to build self-consistent and standardised databases of geological and geochemical information used to archive palaeo sea levels and ice sheets. There are three phases in the development of a database: i) measurement, ii) interpretation, and iii) database creation. Measurement should include the objective description of the position and age of a sample, description of associated geological features, and quantification of uncertainties. Interpretation of the sample may have a subjective component, but it should always include uncertainties and alternative or contrasting interpretations, with any exclusion of existing interpretations requiring a full justification. During the creation of a database, an approach based on Accessibility, Transparency, Trust, Availability, Continuity, Completeness and Communication of content (ATTAC^3) must be adopted. It is essential to consider the community that creates and benefits from a database. We conclude that funding agencies should not only consider the creation of original data in specific research-question oriented projects, but also include the possibility of using part of the funding for IT-related and database creation tasks, which are essential to guarantee accessibility and maintenance of the collected data.

1 Introduction

The rapid acquisition of palaeoclimate data and the development of strategies to assimilate this data into models has resulted in a growing need for open-access and user-friendly databases with the goal of machine readability (Overpeck et al., 2011). Within the palaeo sea-level and ice-sheet communities, there is the further requirement of standardisation (Hijma et al., 2015). These communities use field data to reconstruct the elevation of past sea levels and the dimensions and extent of former ice sheets. As an example of assimilation of data into models, databases of sea-level index points have constrained model estimates of the rates of glacial isostatic adjustment (GIA) during and following the last deglaciation (e.g., Bradley et al., 2011; Whitehouse et al., 2012; Peltier et al., 2015; Roy and Peltier, 2015; Milne et al., 2005; Engelhart et al., 2011). The results from these studies have contributed, in turn, to estimating current rates of ice-sheet mass loss and sea-level rise from geodetic observations (Vaughan et al., 2013). Other databases have been used to assess the magnitude of the sea-level highstand during the last interglacial period (Dutton and Lambeck, 2012; Kopp et al., 2009) and improve our understanding of global ocean volume and earth dynamic topography during the Pliocene (Rowley et al., 2013; Rovere et al., 2014, 2015). Likewise, the worldwide timing of the Last Glacial Maximum (e.g., Clark et al., 2009) and global deglaciation of valley glaciers (e.g., Shakun et al., 2015) has been determined from ice-sheet databases.

The generation of databases of past sea-level changes began with Daly (1934) and Godwin (1940), with early examples of reconstructing temporal changes in former ice-sheet margins by Prest et al. (1968) and Bryson et al. (1969). The need for standardisation among studies as new sea-level data emerged was recognised and implemented by IGCP projects, starting with IGCP Project 61 in 1974 (van de Plassche, 1986). Subsequent IGCP projects produced Holocene databases in the United Kingdom (Shennan and Horton, 2002), the US Atlantic Coast (Engelhart and Horton, 2012), South America (Milne et al., 2005) and elsewhere (Khan et al., 2015). Several recent studies have constructed deglacial databases of ice-sheet retreat, but used different criteria and approaches to data assimilation (e.g., Dyke, 2004; Clark et al., 2009; Tarasov et al., 2012; Briggs et al., 2014; Hughes et al., 2016; Stokes et al., 2015; Stroeven et al., in press).

The process of setting up a sea-level or ice sheet database can be divided into three phases: i) measurement, ii) interpretation, and iii) database creation. In this paper, we build on the results of PALSEA (PALeo constraints on SEA level rise, Siddall et al. (2010)) workshops over the last eight years to report the main challenges identified for each phase and the possible solutions that can be adopted.

2 Measurements

A common denominator of palaeo sea-level and ice-sheet data is that they originate from two types of direct measurements. Field measurements are taken to determine the position, location and elevation of a particular feature (e.g., a fossil coral or a glacial deposit). Meta data, such as cross sections and photographs, may also be used to illustrate the local geological and geomorphological context. Laboratory measurements include establishing the age of a feature (e.g., a ^{14}C or cosmogenic surface exposure age), which was sampled in the field. Sample information on location, elevation and shielding for cosmogenic surface exposure ages is critical for recalculation of ages as inferred production rates change (Balco, 2011).

Any measurement of palaeo sea-level and ice-sheet data needs clearly specified uncertainties. The scientific value of the data is maximised if uncertainties are reduced, but missing information often exacerbates uncertainties. For example, uncertainties related to the elevation of a sea-level index point are potentially large if the original study did not indicate the tidal or geodetic datums to which the elevation is referenced (van de Plassche, 1986). Elevation errors can greatly affect palaeo RSL calculations, and can be avoided by employing state-of-the-art GPS and leveling techniques (e.g., Rovere et al., 2015; Muhs et al., 2011). Despite this, high-accuracy GPS systems are to date seldom applied to measure Quaternary and Pliocene sea-level proxies. Although the laboratory error is often indicated as part of laboratory procedures, this is not always the case with instrumental errors in a field measurement.

Ideally, multiple studies measuring and interpreting the same proxy should have overlapping uncertainty ellipses (cases 1 and 2 in Figure 1a). Unfortunately, there are many examples where measurements do not overlap (3 in Fig. 1a), or cannot be realistically compared due to the lack of details on measurement techniques or details on interpretation (4 in Fig. 1a). In the worst case, some studies may fail to report the error and cannot therefore compared. Incomplete data limits the longevity of some data, requiring new studies to re-measure the same proxies.

Measurement of palaeo sea-level and ice-sheet data can either be obtained by direct field or laboratory activities, or derived from a previous publication and inserted in the database. In all cases, the transfer of information should be objective and complete, reporting only what can be read in the original publication and/or what is measured in the field, with no further interpretation. An important goal for the future is for different communities to agree on standardised measurements and data reporting norms (e.g., Hijma et al., 2015). Precision of terminology is vital to avoid misinterpretations of field and laboratory measurements (Shennan et al., 2015). This will facilitate seamless interfacing with database systems for archiving and further analysis. Palaeo sea-level and ice-sheet databases need to include standardised documentation of fundamental data fields:

Position (geographical location and elevation or depth, associated with a specific sea-level datum to which the elevation is referred) and, if available, the positioning techniques applied.

Age, including lab identification number, details on the dating technique used and ideally the raw data;

Description of the feature, including metadata and images to complement the quantitative information;

Quantification of measurement uncertainties.

3 Interpretation

Once measured, field and laboratory data are interpreted to reconstruct the palaeo sea level and the spatial and temporal extent of the palaeo ice sheet. Commonly it is the interpretations that will be most interesting for the final users, who may not be experts, but need to compare the reconstructions with independent estimates, such as model predictions.

There is often a subjective component to the interpretation of field data. In Fig. 1b, we show fossil corals, a typical example of a sea-level indicator. An objective assessment of the coral age can be determined using U-series techniques (e.g., applying the template used in Dutton and Lambeck, 2012). The position of the deposit relative to a tidal or geodetic datum can be measured with appropriate accuracy. The taxonomy of the sample can be reported, which should include information on the benthic assemblage ad its relation to sea level, geological and sedimentological properties. The subjectivity relates to the interpretation of the palaeowater depth (i.e., relation to sea level) of the coral. One possible interpretation following investigation of the depth distribution of corals in the deposit is that the corals are in situ (e.g. in living position), and sea level at the time of deposition was somewhere above the measured elevation (i.e., it is a lower limiting data point, Int.1 in Fig. 1b). Another interpretation could be that the corals are allochthonous, and instead represent a storm deposit. In this case, it is only possible to infer that the deposit represents the top of a marine sequence, and the palaeo sea level was located below the measured elevation of the deposit (i.e., it is upper limiting data point, Int.2 in Fig. 1b). A final interpretation may instead recognise elements (e.g., microatolls, intertidal geological facies within the deposit) that tie the deposit to the palaeo sea level around the measured elevation within an uncertainty (i.e., identifying reference water level and indicative range (Shennan, 1986; van de Plassche, 1986; Horton et al., 2000), Int.3 in Fig. 1b). Whenever controversial interpretations such as those summarised above exist, a database should document all of them. If one interpretation is more likely than the others, or is supported by independent studies, this information should be inserted in the database within the metadata.

Issues may emerge in the interpretation of laboratory data, such as the use of different calibration curves to establish the age of an indicator. The interpretation of data can be subject to changes with scientific advances. As an example, old ^{14}C ages or cosmogenic surface exposure ages can be re-calibrated following the availability of new calibration curves or calibration schemes or new production rates and scaling models, respectively. But the possibility of recalibrating these measurements depends on the presence of primary data, such as δ^{13}C measurements, description of the dated material, sample thickness, etc. (Balco, 2011; Törnqvist et al., 2015). In principle, if measurement data are present in a database, obtaining secondary data from new interpretations can be streamlined relatively easily.

Uncertainties of sea-level and ice-sheet indicators are usually treated as Gaussian distributions, with the exception of limiting data that only provide information on maximum or minimum sea level (Int.1 and Int.2 in Fig. 1b). In the case of Gaussian uncertainties, the uncertainty of the interpretation can be combined with the uncertainty of the measurement (dashed line in Fig. 1b) using the root mean square error formula (assuming the uncertainties are independent; more complicated uncertainties may require Monte Carlo sampling). As understanding of habitat distribution for marine species or coastal facies increases, and more consideration is given to the physical processes that perturb sample elevation over time, an increasing amount of data will use more accurate uncertainty distributions that extend beyond the Gaussian approximation. We recommend recording multiple percentiles of these non-Gaussian distributions, to reflect not only the width of the uncertainty, but also the shape of its probability distribution.

Palaeo sea-level and ice-sheet databases that incorporate interpretations must therefore be:

- Flexible to take into account the fact that although the measurement must be unequivocal, interpretation of the data can be multiple, and vary or evolve over time;
- Consistent in the reporting of interpretations and uncertainties of data.

4 Database creation

A database is primarily a collection of data records and secondarily a platform for exchange of data and information. The process of creating a database must necessarily start from the identification of the agents that will interact with it. Data creators provide the original datasets, and should carry out their work with databases in mind. In palaeoclimate sciences, these are usually geologists and geochemists, who carry out the main part of the measurement and interpretation process. Data compilers collect data from different sources and, if necessary, reinterpret it. Measurement and interpretation constitute the backbone of every palaeo sea-level and ice-sheet database, but there are other key elements to be considered, which we summarise under the **ATTAC^{3}** acronym (Fig. 1c): **A**ccessibility, **T**ransparency, **T**rust, **A**vailability, **C**ontinuity, **C**ompleteness and **C**ommunication of content.

Accessibility is a challenge due to the heterogeneity of the user communities. A majority of published databases today are using spreadsheet format, which are easy to access for most users. However, some information (e.g., images or non-Gaussian uncertainty estimates) is more simply presented in relational databases. Furthermore, relational databases enable different presentation formats for different end-user communities.

Transparency is critical in interdisciplinary research fields. Scientists must trust each other on the applied methodology, but at the same time have to be able to understand the applied procedures. As a database creator and compiler cannot know all future users of the data and the fields in which they are applied, the database description must be as detailed as possible. The description should include appropriate metadata and use of standardised language and comments in data fields. Indicating the quality of each data field in understandable formats will help the end user to make appropriate use of the data (Düsterhus and Hense, 2014).

Trust is built by database compilers sharing credit with the scientists delivering the data (Costello, 2009; Kattage et al., 2014). Data creators and compilers are confronted with the risk that their original publications are no longer cited when their data is included into a larger citable database, and thus will not gain credit under current performance metrics, such as the H-index (Hirsch, 2005). To ensure the availability of high quality datasets in the future, data creators need to be given appropriate credit. Trust of a database requires consistent data quality and transparently applied procedures, and a consistent and trustworthy host. It also requires effective software design for the database and within the data processing. Ideally, the code should be openly available and well documented.

Availability of a database for the long-term requires long-term funding (see below). Today, most databases are attached to journal articles as a spreadsheet in the supplement. This ensures persistence, but no database maintenance and/or upgrade is possible for most journals.

Continuity of updating is important to stay relevant and reflect the changing interpretations of the data. To allow cite-ability of the database (e.g., with Digital Object Identifiers (DOI); Paskin, 2005; Quadt et al., 2012), version control is essential. Furthermore, the use of unique identifiers, such as the International Geo Sample Number (IGSN) that is currently used for geological samples, should be encouraged to ensure that over different update cycles, a data point can be uniquely referenced by scientists.

Completeness of the database is important, especially in the context of uncertainties (Hijma et al., 2015). Even when the basic elements (like position, age and elevation) are complete, for many applications they are of limited use when associated uncertainties are not clearly indicated or defined.

Communication of the content, for example through interfaces for visualisation software, helps to open the database for new audiences. Advanced visualisation approaches (e.g., Unger et al., 2012; Rovere et al., 2012) require standardised protocols for data extraction and consistent data types. These properties have to be determined in the design phase of the database, thus it is important to consider its applications right from the beginning.

5 The community structure

Any database should be aimed at serving a community of end-users, who extract content for further analysis, and give feedback on specific needs regarding datasets or analyses. Databases should be centralised and interconnected via the Internet in order to reach the maximum possible number of end-users, with the widest possible geographic distribution. The data is more likely to be used if the end-users have a unique access point for the datasets, such as a WebGIS portal. In the geological domain, there are large initiatives to build data repositories, which are already well established and used by scientists worldwide. Two examples are the NOAA World Data Center for Paleoclimatology (Wahl et al., 2010) and PANGAEA. Some journals link PANGAEA databases to online versions of associated papers.

Most funding agencies require that data collected in the framework of a project are archived and made available through data repositories. This is achieved through a ’Data Management Plan’ (National Science Foundation of the United States) or the ’Open Data Policy’ (European Union), which requests that the project leaders state where they plan to store the data collected within their project. Currently, a researcher working on sea-level and/or ice-sheet databases only has the choice to store the new datasets in different repositories, which might have the effect of dispersing the data across several repositories, decentralising data storage (see example in Fig. 3).

In the framework of a single research project, the data creator is also a data compiler, and often the first end-user. It is, therefore, necessary to ensure that the datasets collected in the framework of a single project have a standardised structure and are available to other end users.

A significant concern regarding the maintenance of a healthy research community is appropriate crediting of authorship. How does an end-user using thousands of data points from dozens of source publications provide appropriate credit? Journals often allow for only a limited number of citations, and often the citation credit goes to the data compiler, who created the review database, and not to the data creator. If the question above is not addressed, the long-term result will be that data creators will have no incentive to support the inclusion of their work in a centralised database. This issue must be addressed by journal editors. In some cases, editors have made exceptions to standard journal length rules in order to include all the original papers in the reference list (e.g., Khan et al., 2015). Alternatively, some journals allow longer, online-only papers with space for a full reference list (e.g., Kopp et al., in press).

A number of sea-level databases have been produced in the framework of single research projects (Table 1). In general, there are two formats in which the data are provided: data repositories in the form of spreadsheets (R) and interactive interfaces that allow the visualisation, extraction or download of data (I). In Fig. 2 we show the geographic location of databases of Holocene RSL data compiled from different original studies following the IGCP guidelines, where each index point has a defined location, age, elevation relative to former sea level, and appropriate accounting of uncertainties (details to the databases in Table 2).

6 Concluding Remarks

The discussions of the PALSEA community on sea-level and ice sheets databases can be framed around the following points:

1. Any set-up of sea-level or ice-sheet databases must be divided into: i) measurement; ii) interpretation; and iii) database creation.

2. Storage of measurements should include position, age, description of geological features, and quantification of uncertainties. All must be described as objectively as possible with relevant metadata.

3. Interpretation of geological data will retain a subjective component, but it should always include uncertainties and include all the possible interpretations.

4. When creating a database, all the aspects related to the ATTAC^3 (Accessibility, Transparency, Trust, Availability, Continuity, Completeness, Communication) approach must be taken into account.

5. The community structure that creates and benefits from a database must be considered, and the needs and concerns of each part of the community must be respected.

There remains the need for a centralised database structure for the sea-level and ice-sheet communities. Despite this need, dedicated funding for 'user friendly', field-specific database creation is rarely available because funding mostly prioritises projects that follow the classic hypothesis-driven research approach. Data management is often restricted to archiving at a general level. The tasks of database creation, maintenance and guarantee of accessibility are limited to single projects and the possibility to hire ad hoc personnel (e.g., experts in geoinformatics) to fulfil these requirements is often disregarded by funding agencies. We favour interdisciplinary research collaborations focusing on field-specific database development and maintenance, including projects that amalgamate and reanalyse published datasets into new databases. These new databases enhance the legacy of monetary investments originally made to collect sea-level and ice-sheet data. Many of the aspects discussed in this paper will also be valid for other types of geological data and may be of interest to additional geoscientific communities.

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References

Balco, G.: Contributions and unrealized potential contributions of cosmogenic-nuclide exposure dating to glacier chronology, 1990–2010, Quaternary Science Reviews, 30, 3–27, doi:10.1016/j.quascirev.2010.11.003, 2011.

Bradley, S. L., Milne, G. A., Shennan, I., and Edwards, R.: An improved glacial isostatic adjustment model for the British Isles, Journal of Quaternary Science, 26, 541–552, doi:10.1002/jqs.1481, 2011.

Briggs, R. D. and Tarasov, L.: How to evaluate model-derived deglaciation chronologies: a case study using Antarctica, Quaternary Science Reviews, pp. 109–127, doi:10.1016/j.quascirev.2012.11.021, 2013.

Briggs, R. D., Pollard, D., and Tarasov, L.: A data-constrained large ensemble analysis of Antarctic evolution since the Eemian, Quarternary Science Reviews, 103, 91–115, doi:10.1016/j.quascirev.2014.09.003, 2014.

Brooks, A. and Edwards, R.: The Development of a Sea-Level Database for Ireland, Irish Journal of Earth Science, 24, 13–27, doi:10.3318/ijes.2006.24.1.13, 2006.

Bryson, R. A., Wendland, W. M., Ives, J. D., and Andrews, J. T.: Radiocarbon Isochrones on the Disintegration of the Laurentide Ice Sheet, Arctic and Alpine Research, 1, 1–14, doi:10.2307/1550356, 1969.

Clark, P. U., Dyke, A., Shakun, J. D., Carlson, A. E., Clark, J., Wohlfarth, B., Hostetler, S., Mitrovica, J. X., and McCabe, A.: The Last Glacial Maximum, Science, 325, 710–714, doi:10.1126/science.1172873, 2009.

Clement, A. J., Whitehouse, P. L., and Sloss, C. R.: An examination of spatial variability in the timing and magnitude of Holocene relative sea-level changes in the New Zealand archipelago, Quaternary Science Reviews, 131, 73–101, doi:10.1016/j.quascirev.2015.09.025, 2016.

Costello, M. J.: Motivating Online Publication of Data, BioScience, 59, 418–427, doi:10.1525/bio.2009.59.5.9, 2009.

Daly, R. A.: The changing world of the ice age, Yale University Press, New Haven, doi:http://dx.doi.org/10.1017/s001675680009422x, 1934.

Düsterhus, A. and Hense, A.: Automated quality evaluation for a more effective data peer review, Data Science Journal, 13, 67–78, doi:10.2481/dsj.14-009, 2014.

Dutton, A. and Lambeck, K.: Ice Volume and Sea Level During the Last Interglacial, Science, 337, 216–219, doi:10.1126/science1205749, 2012.

Dyke, A. S.: An outline of North American Deglaciation with emphasis on central and northern Canada, in: Quaternary Glaciations - Extent and Chronology: Part II: North America, edited by Ehlers, J. and Gibbard, P. L., pp. 373–424, Elsevier, Amsterdam, doi:10.1016/S1571-0866(04)80209-4, 2004.

Engelhart, S. and Horton, B. P.: Holocene sea level database for the Atlantic coast of the United States, Quarternary Science Reviews, 54, 12–25, doi:10.1016/j.quascirev.2011.09.013, 2012.

Engelhart, S., Peltier, W. R., and Horton, B. P.: Holocene relative sea-level changes and glacial isostatic adjustment of the U.S. Atlantic coast, Geology, 39, 751–754, doi:10.1130/G31857.1, 2011.

Engelhart, S. E., Vacci, M., Horton, B. P., Nelson, A. R., and Kopp, R. E.: A sea-level database for the Pacific coast of central North America, Quaternary Science Reviews, 113, 78–92, doi:10.1016/j.quascirev.2014.12.001, 2015.

Godwin, H.: Studies in the post-glacial history of British vegetation. III: Fenland pollen diagrams. IV: Post-glacial changes of relative land and sea level in the English Fenland, Philosophical Transactions of the Royal Society of London B, 230, 239–303, doi:http://dx.doi.org/10.1098/rstb.1940.0001, 1940.

Hijma, M., Engelhart, S., Horton, B. P., Törnqvist, T., Hu, P., and Hill, D.: A protocol for a geological sea-level database, in: Handbook of Sea-Level Research, edited by Shennan, I., Long, A. J., and Horton, B. P., pp. 536–553, Wiley Blackwell, doi:10.1002/9781118452547.ch34, 2015.

Hirsch, J. E.: An index to quantify an individual's scientific research output, Proceedings of the National Academy of Sciences, 102, 16 569–16 572, doi:10.1073/pnas.0507655102, 2005.

Horton, B. P., Edwards, R. J., and Floyd, J. M.: Implications of a microfossil-based transfer function in Holocene sea-level studies, Geological Society Special Publication, 166, 41–54, doi:10.1144/GSL.SP.2000.166.01.03, 2000.

Horton, B. P., Gibbard, P. L., Mine, G. M., Morley, R. J., Purintavaragul, C., and Stargardt, J. M.: Holocene sea levels and palaeoenvironments, Malay-Thai Peninsula, southeast Asia, The Holocene, 15, 1199–1213, doi:10.1191/0959683605hl891rp, 2005.

Hughes, A. L. C., Gyllencreutz, R., Lohne, Ø. S., Mangerud, J., and Svendsen, J. I.: The last Eurasian ice sheets – a chronological database and time-slice reconstruction, DATED-1, Boreas, 45, 1–45, doi:10.1111/bor.12142, 2016.

Kattage, J., Diaz, S., and Wirth, C.: Of carrots and sticks, Nature Geoscience, 7, 778–779, doi:10.1038/ngeo2280, 2014.

Khan, N. S., Ashe, E., Shaw, T. A., Vacchi, M., Walker, J., Peltier, W., Kopp, R. E., and Horton, B. P.: Holocene Relative Sea-Level Changes from Near-, Intermediate-, and Far-Field Locations, Current Climate Change Reports, 1, 247–262, doi:10.1007/s40641-015-0029-z, 2015.

Klemann, V., Unger, A., Hibbert, F., and Dransch, D.: SLIVISU, a concept of an interactive visualization framework for the analysis of geological data, in: EGU General Assembly Conference Abstracts, vol. 15, pp. EGU2013–13 953, Vienna, 2013.

Kopp, R. E., Simons, F. J., Mitrovica, J. X., Maloof, A. C., and Oppenheimer, M.: Probabilistic assessment of sea level during the last interglacial stage, Nature, pp. 863–867, doi:10.1038/nature08686, 2009.

Kopp, R. E., Kemp, A. C., Bittermann, K., Horton, B. P., Donnelly, J. P., Hay, C. C., Mitrovica, J. X., Morrow, E. D., and Rahmstorf, S.: Global sea-level variability in the Common Era, Proceedings of the National Academy of Sciences, in press.

Long, A. J., Woodroffe, S. A., Roberts, D. H., and Dawson, S.: Isolation basins, sea-level changes and the Holocene history of the Greenland Ice Sheet, Quaternary Science Reviews, 30, 3748–3768, doi:10.1016/j.quascirev.2011.10.013, 2011.

Milne, G. A., Long, A. J., and Bassett, S. E.: Modelling Holocene Relative Sea-Level Observations from the Caribbean and South America, Quarternary Science Reviews, 24, 1183–1202, doi:10.1016/j.quascirev.2004.10.005, 2005.

Muhs, D. R., Simmons, K. R., Schumann, R. R., and Halley, R. B.: Sea-level history of the past two interglacial periods: new evidence from U-series dating of reef corals from south Florida, Quaternary Science Reviews, 30, 570–590, doi:10.1016/j.quascirev.2010.12.019, 2011.

Overpeck, J. T., Meehl, G. A., Bony, S., and Easterling, D. R.: Climate data challenges in the 21st century, Science, 331, 700–702, doi:http://dx.doi.org/10.1126/science.1197869, 2011.

Paskin, N.: Digital Object Identifiers for scientific data, Data Science Journal, 4, 12–20, doi:http://dx.doi.org/10.2481/dsj.4.12, 2005.

Pedoja, K., Husson, L., Johnson, M. E., Melnick, D., Witt, C., Pochat, S., Nexer, M., Delcaillau, B., Pinegina, T., Poprawski, Y., Authemayou, C., Elliot, M., Regard, V., and Garestier, F.: Coastal staircase sequences reflecting sea-level oscillations and tectonic uplift during the Quaternary and Neogene, Earth-Science Reviews, 132, 13–38, doi:10.1016/j.earscirev.2014.01.007, 2014.

Peltier, W. R., Argus, D. F., and Drummond, R.: Space geodesy constrains ice age terminal deglaciation: The global ICE-6G_C (VM5a) model, Journal of Geophysical Research: Solid Earth, 120, 450–487, doi:10.1002/2014JB011176, 2015.

Prest, V., Grant, D. R., and Rampton, V. N.: Gacial Map of Canada, Map 1532A, Ottawa, doi:http://dx.doi.org/10.4095/108979, 1968.

Quadt, F., Düsterhus, A., Höck, H., Lautenschlager, M., Hense, A. V., Hense, A. N., and Dames, M.: Atarrabi - A workflow system for the Publication of Envrionmental Data, Data Science Journal, 11, 89–109, doi:10.2481/dsj.012-027, 2012.

Reynolds, L. C. and Simms, A. R.: Late Quaternary relative sea level in Southern California and Monterey Bay, Quaternary Science Reviews, 126, 57–66, doi:10.1016/j.quascirev.2015.08.003, 2015.

Rovere, A., Raymo, M. E., O'Leary, M. J., and Hearty, P. J.: Crowdsourcing in the Quaternary sea level community: insights from the Pliocene, Quaternary Science Reviews, 56, 164–166, doi:10.1016/j.quascirev.2012.09.014, 2012.

Rovere, A., Raymo, M. E., Mitrovica, J. X., Hearty, P. J., O'Leary, M. J., and Inglis, J. D.: The Mid-Pliocene sea-level conundrum: Glacial isostasy, eustasy and dynamic topography, Earth and Planetary Science Letters, 387, 27–33, doi:10.1016/j.epsl.2013.10.030, 2014.

Rovere, A., Hearty, P. J., Austermann, J., Mitrovica, J. X., Gale, J., Moucha, R., Forte, A. M., and Raymo, M. E.: Mid-Pliocene shorelines of the US Atlantic Coastal Plain—An improved elevation database with comparison to Earth model predictions, Earth-Science Reviews, 145, 117–131, doi:10.1016/j.earscirev.2015.02.007, 2015.

Rowley, D. B., Forte, A. M., Moucha, R., Mitrovica, J. X., Simmons, N. A., and Grand, S. P.: Dynamic Topography Change of the Eastern United States Since 3 Million Years Ago, Science, 340, 1560–1563, doi:10.1126/science.1229180, 2013.

Roy, K. and Peltier, W. R.: Glacial isostatic adjustment, relative sea level history and mantle viscosity: reconciling relative sea level model predictions for the U.S. East coast with geological constraints, Geophysical Journal International, 201, 1156–1181, doi:10.1093/gji/ggv066, 2015.

Shakun, J. D., Clark, P. U., He, F., Lifton, N. A., Liu, Z., and Otto-Bliesner, B. L.: Regional and global forcing of glacier retreat during the last deglaciation, Nature Communications, 6, doi:10.1038/ncomms9059, 2015.

Shennan, I.: Flandrian sea-level changes in the Fenland. II: Tendencies of sea-level movement, altitudinal changes, and local and regional factors, Journal of Quaternary Science, 1, 155–179, doi:10.1002/jqs.3390010205, 1986.

Shennan, I. and Horton, B.: Holocene land- and sea-level changes in Great Britain, Journal of Quaternary Science, 17, 511–526, doi:10.1002/jqs.710, 2002.

Shennan, I., Long, A. J., and Horton, B. P., eds.: Handbook of Sea-Level Research, Wiley Blackwell, doi:10.1002/9781118452547, 2015.

Siddall, M., Abe-Ouchi, A., Andersen, A., Antonioli, F., Bamber, J. L., Bard, E., Clark, J., Clark, P. U., Deschamps, P., Dutton, A., Elliot, M., Gallup, C., Gomez, N., Gregory, J. M., Huybers, P., Kawarnura, K., Kelly, M., Lambeck, K., Lowell, T., Mitrovica, J. X., Otto-Bliesner, B. L., Richards, D., Stanford, J. R., Stirling, C., Stocker, T. F., Thomas, A. L., Thompson, B., Tornqvist, T., Riveiros, N., Waelbroeck, C., Yokoyama, Y., and Yu, S. U.: The sea-level conundrum: case studies from palaeo-archives, Journal of Quarternary Science, 25, 19–25, doi:10.1002/jqs.1270, 2010.

Stokes, C. R., Tarasov, L., Blomdin, R., Cronin, T. M., Fisher, T. G., Gyllencreutz, R., Hättestrand, C., Heyman, J., Hindmarsh, R. C., Hughes, A. L., Jakobsson, M., Kirchner, N., Livingstone, S. J., Margold, M., Murton, J. B., Noormets, R., Peltier, W. R., Peteet, D. M., Piper, D. J., Preusser, F., Renssen, H., Roberts, D. H., Roche, D. M., Saint-Ange, F., Stroevend, A. P., and Tellert, J. T.: On the reconstruction of palaeo-ice sheets: Recent advances and future challenges, Quarternary Science Reviews, 125, 15—-49, doi:10.1016/j.quascirev.2015.07.016, 2015.

Stroeven, A. P., Hättestrand, C., Kleman, J., Heyman, J., Fabel, D., Fredin, O., Goodfellow, B. W., Harbor, J. M., Jansen, J. D., Olsen, L., Caffee, M. W., Fink, D., Lundqvist, J., Rosqvist, G. C., Strömberg, B., and Jansson, K. N.: Deglaciation of Fennoscandia, Quarternary Science Reviews, doi:10.1016/j.quascirev.2015.09.016, in press.

Tarasov, L., Dyke, A., Neal, R. M., and Peltier, W. R.: A data-calibrated distribution of deglacial chronologies for North American ice complex from glaciological modelling, Earth and Planetary Science Letters, 315–316, doi:10.1016/j.epsl.2011.09.010, 2012.

Törnqvist, T. E., Rosenheim, B. E., Hu, P., and Fernandez, A. B.: Radiocarbon dating and calibration, in: Handbook of Sea-Level Research, edited by Shennan, I., Long, A. J., and Horton, B. P., pp. 349—-360, Wiley Blackwell, doi:10.1002/9781118452547.ch23, 2015.

Unger, A., Schulte, S., Klemann, V., and Dransch, D.: Visual Analytics Concept for the Validation of Geoscientific Simulation Models, IEEE Trans. Vis. Comp. Graph, 18, 2216–2225, doi:http://dx.doi.org/10.1109/tvcg.2012.190, 2012.

Vacchi, M., Rovere, A., Chatzipetros, A., Zouros, N., and Firpo, M.: An updated database of Holocene relative sea level changes in NE Aegean Sea, Quaternary International, 328–329, 301–310, doi:10.1016/j.quaint.2013.08.036, 2014.

Vacchi, M., Marriner, N., Morhange, C., Spada, G., Fontana, A., and Rovere, A.: Multiproxy assessment of Holocene relative sea-level changes in the western Mediterranean: variability in the sea-level histories and redefinition of the isostatic signal., Earth-Science Reviews, accepted.

van de Plassche, O.: Sea-level research: a manual for the collection and evaluation of data, Springer Netherlands, doi:10.1007/978-94-009-4215-8, 1986.

Vaughan, D. G., Comiso, J., Allison, I., Carrasco, J., Kaser, G., Kwok, R., Mote, P., Murray, T., Paul, F., Ren, J., Rignot, E., Solomina, O., Steffen, K., and Zhang, T.: Observations: Cryosphere, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2013.

Vink, A., Steffen, H., Reinhardt, L., and Kaufmann, G.: Holocene relative sea-level change, isostatic subsidence and the radial viscosity structure of the mantle of northwest Europe (Belgium, the Netherlands, Germany, southern North Sea), Quaternary Science Reviews, 26, 3249–3275, doi:10.1016/j.quascirev.2007.07.014, 2007.

Wahl, E. R., Anderson, D. M., Bauer, B. A., Buckner, R., Gille, E. P., Gross, W. S., Hartman, M., and Shah, A.: An archive of high-resolution temperature reconstructions over the past 2+millennia, Geochemistry, Geophysics, Geosystems, 11, doi:10.1029/2009GC002817, 2010.

Whitehouse, P. L., Bentley, M. J., and Le Brocq, A. M.: A deglacial model for Antarctica: geological constraints and glaciological modelling as a basis for a new model of Antarctic glacial isostatic adjustment, Quaternary Science Reviews, 32, 1–24, doi:10.1016/j.quascirev.2011.11.016, 2012.

Zong, Y.: Mid-Holocene sea-level highstand along the Southeast Coast of China, Quaternary International, 117, 55–67, doi:10.1016/S1040-6182(03)00116-2, 2004.

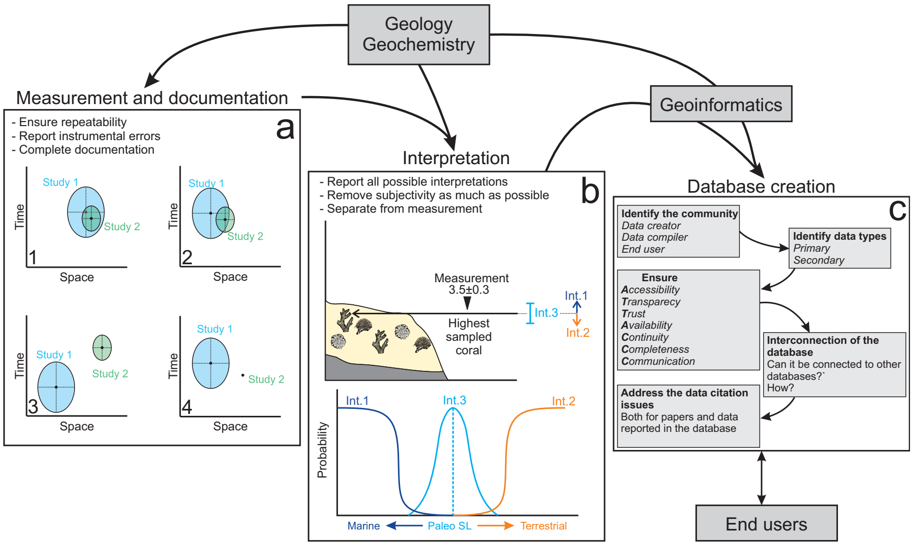


Figure 1. a) The effect of different measurement and documentation of time and space of the same sea-level indicator in two different studies. b) Different interpretations for the sea-level indicator: a deposit containing fossil corals. c) ATTAC3 approach to database creation. See text for details.

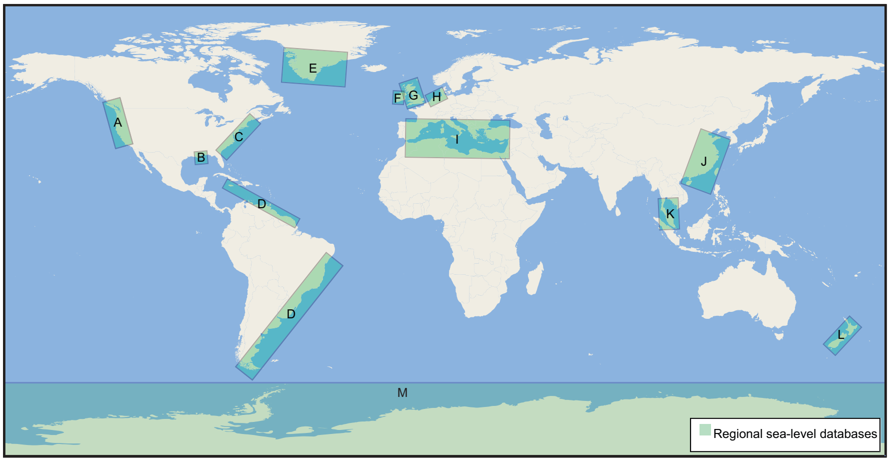
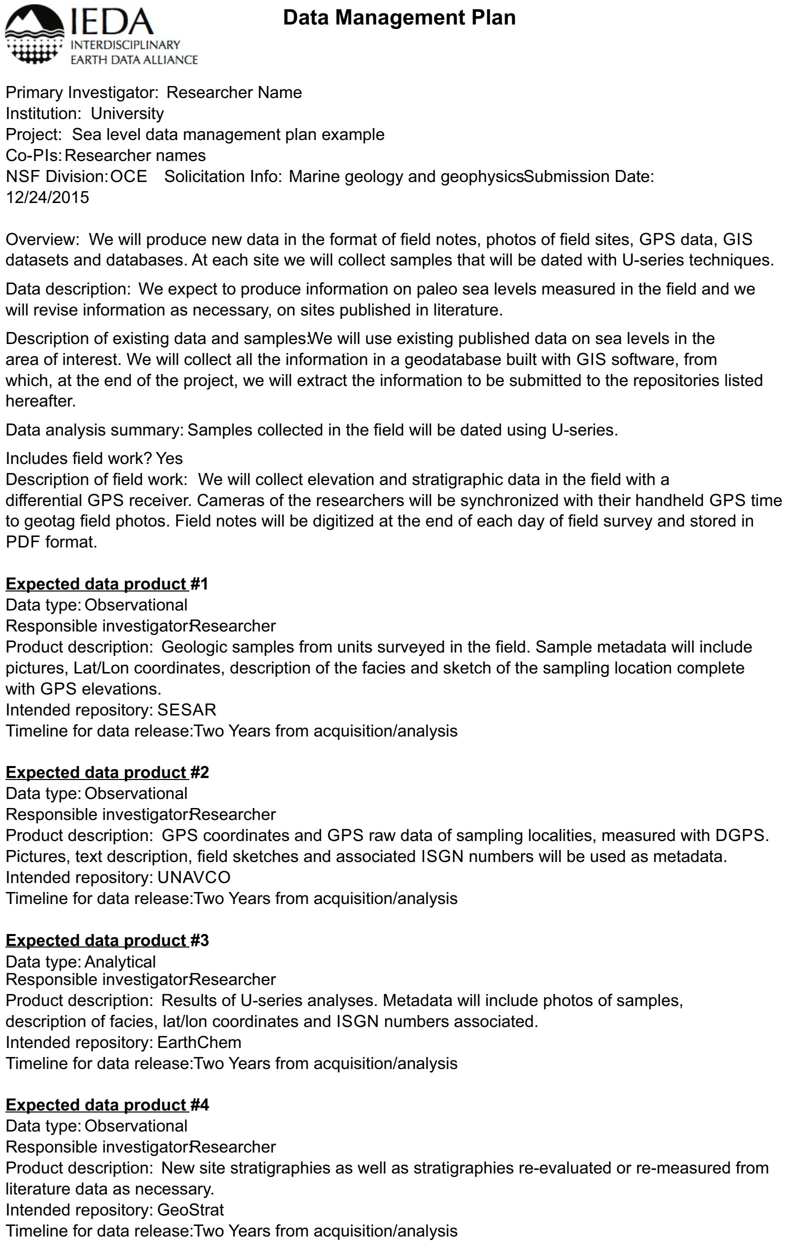


Figure 2. Published regional sea-level databases that follow (where appropriate) IGCP guidelines: (A) Pacific (Engelhart et al., 2015); Reynolds and Simms (2015)), (B) Gulf (Hijma et al., 2015)) and (C) Atlantic (Engelhart and Horton, 2012)) coasts of North America, (D) Caribbean and South America (Milne et al., 2005)), (E) Greenland (Long et al., 2011)), (F) Ireland (Brooks and Edwards, 2006)), (G) the UK (Shennan and Horton, 2002)), (H) northwest Europe (Vink et al., 2007)), (I) the Mediterranean (Vacchi et al., 2014); Vacchi et al. (accepted)), (J) China (Zong, 2004)), (K) Malay-Thai Peninsula (Horton et al., 2005)), (L) New Zealand (Clement et al., 2016)), and (M) Antarctica (Briggs and Tarasov, 2013)).



IEDA INTERDISCIPLINARY EARTH DATA ALLIANCE

Data Management Plan

Primary Investigator: Researcher Name
Institution: University
Project: Sea level data management plan example
Co-PIs: Researcher names
NSF Division: OCE Solicitation Info: Marine geology and geophysics Submission Date: 12/24/2015

Overview: We will produce new data in the format of field notes, photos of field sites, GPS data, GIS datasets and databases. At each site we will collect samples that will be dated with U-series techniques.

Data description: We expect to produce information on paleo sea levels measured in the field and we will revise information as necessary, on sites published in literature.

Description of existing data and samples: We will use existing published data on sea levels in the area of interest. We will collect all the information in a geodatabase built with GIS software, from which, at the end of the project, we will extract the information to be submitted to the repositories listed hereafter.

Data analysis summary: Samples collected in the field will be dated using U-series.

Includes field work? Yes
Description of field work: We will collect elevation and stratigraphic data in the field with a differential GPS receiver. Cameras of the researchers will be synchronized with their handheld GPS time to geotag field photos. Field notes will be digitized at the end of each day of field survey and stored in PDF format.

Expected data product #1
Data type: Observational
Responsible investigator: Researcher
Product description: Geologic samples from units surveyed in the field. Sample metadata will include pictures, Lat/Lon coordinates, description of the facies and sketch of the sampling location complete with GPS elevations.
Intended repository: SESAR
Timeline for data release: Two Years from acquisition/analysis

Expected data product #2
Data type: Observational
Responsible investigator: Researcher
Product description: GPS coordinates and GPS raw data of sampling localities, measured with DGPS. Pictures, text description, field sketches and associated ISGN numbers will be used as metadata.
Intended repository: UNAVCO
Timeline for data release: Two Years from acquisition/analysis

Expected data product #3
Data type: Analytical
Responsible investigator: Researcher
Product description: Results of U-series analyses. Metadata will include photos of samples, description of facies, lat/lon coordinates and ISGN numbers associated.
Intended repository: EarthChem
Timeline for data release: Two Years from acquisition/analysis

Expected data product #4
Data type: Observational
Responsible investigator: Researcher
Product description: New site stratigraphies as well as stratigraphies re-evaluated or re-measured from literature data as necessary.
Intended repository: GeoStrat
Timeline for data release: Two Years from acquisition/analysis

Figure 3. Example of Data management plan for a project on Pleistocene sea-level markers obtained with the IEDA (Interdisciplinary Earth Data Alliance, http://www.iedadata.org/) DMP toolbox. Note that, to correctly store sea-level data, at least four independent repositories are needed.

Table 1. List of published global sea-level databases that follow (where appropriate) the IGCP format. There are two formats in which the data are provided: spreadsheets (R) and interactive interfaces that allow the visualisation, extraction or download of data (I).

Description	Accessibility
Dutton and Lambeck (2012). Compilation of last interglacial coral U-Th age data, elevation data, and associated sample information. The first worksheet of the Excel file contains the data and calculated ages and elevations that have been normalised to common decay constants and elevation benchmarks, respectively; the second worksheet contains definitions of column headings and data units; the third worksheet contains a lookup table for data sources listed by number in the first worksheet. Some entries in the database are annotated by comment fields to denote supplemental information for data or calculations not included in the original publications.	Annexed to publ. (R)
Klemann et al. (2013). Storage of different accessible compilations in relational database system PostgreSQL. Contains the regional databases A, B, C and D shown in Fig. 2 and further data mainly from published compilations or grey literature. Access via Visualisation and analysis software SLIVISU (beta version) or direct access (password protected).	Online (I), on request
Khan et al. (2015). Compilation of global Holocene relative sea-level data. Each database entry includes location, sea level, sea-level error, age, and age error and the original source of publication.	Annexed to publ. (R)
Kopp et al. (2009). Multi-proxy database of last interglacial index and limiting relative sea-level indicators. A legend worksheet defines column headings and data units.	Annexed to publ. (R)
Kopp et al. (in press). Database of Common Era (Last 2000 years) relative sea-level data. Each database entry includes location, sea level, sea-level error, age, and age error and the original source publication. There is a front page of definitions of column headings and data units.	Online (R)
Pedoja et al. (2014). Spreadsheets containing information on shoreline analysis from Holocene to Miocene highstands. Regarding ages, only stratigraphic units are given.	Annexed to publ. (R)
Rovere et al. (2012) [//pliomax.org/pliowiki/index.php/RSLmap]. RSLmap is a visualisation tool for RSL markers, which allows the display and querying of a database of published or user-submitted relative sea level data points.	Online (I)

Table 2. Description of regional databases presented in Figure 2. For details see Table 1

Region	Description	Accessibility
A	**Engelhart et al. (2015); Reynolds and Simms (2015)**. [//sealevel.marine.rutgers.edu/]. Deglacial sea-level database for the Pacific coast of central North America	online (R)
B	**Hijma et al. (2015)**. [//www.ncdc.noaa.gov/cdo/f?p=519:1:0:::::P1_STUDY_ID:16361] Pilot database intended as an initial release of Holocene geological relative sea-level data that have been compiled according to a recently developed protocol (Hijma et al., 2015). The database is provided in two versions: a complete version that consists of 77 variables and that includes all the underlying data, as well as a processed version with only the 11 most critical variables. It is anticipated that this latter version will be adequate for most users, while the former provides a full documentation for those who wish to carry out more detailed analyses.	online (R)
C	**Engelhart and Horton (2012)**. [//sealevel.marine.rutgers.edu/] Holocene sea level database for the Atlantic coast of the United States.	online (R)
D	**Milne et al. (2005)**. Deglacial sea level compilation for the Caribbean and South American Atlantic Coast that was compiled for a regional GIA study.	appendix to publication
E	**Long et al. (2011)**. Compilation and own investigations mainly of Holocene isolation basins for Southern Greenland.	table in publication
F	**Brooks and Edwards (2006)**. [//www.naturalscience.tcd.ie/SL_Database.php] Compilation of sea-level data of Ireland, contains detailed spreadsheet and additional information on webpage.	online (R)
G	**Shennan and Horton (2002)**. The database covers Great Britain (England, Scotland, & Wales) and has around 2250 entries. It exists as an ACCESS database, interfaces to convert the information to Excel spreadsheets for regional compilations are available.	from author
H	**Vink et al. (2007)**. Compilation of available data of Belgium, the Netherlands and Germany of the Channel and southern North Sea of about 380 SLIs which are listed in an appendix to the publication.	appendix to publication
I	**Vacchi et al. (2014); Vacchi et al. (accepted)**. [//www.medflood.org/results-2/webgis/] Published Pleistocene and Holocene sea level data in the Mediterranean Sea collected by the INQUA MEDFLOOD project. online (I)	
J	**Zong (2004)**. Compilation of SLIs covering SE coast of China. There are only a few attributes listed.	appendix to publication
K	**Horton et al. (2005)**. [//sealevel.marine.rutgers.edu/] Holocene sea levels database of Malay-Thai Peninsula, Southeast Asia.	online (R)
L	**Clement et al. (2016)**. Compilation of Holocene sea level data of New Zealand.	table in publication
M	**Briggs and Tarasov (2013)**. Compilation of late glacial and Holocene sea level data of Antarctica.	table in publication