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SeeLevelViz: a simple data science tool for dynamic visualization of shoreline displacement caused by sea-level change

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Abstract

We present SeeLevelViz, a free, open-source program written in Python for making interactive visualizations of relative sea-level change in landscapes and shorelines. The accurate reconstruction of shoreline positions is a crucial factor in coastal palaeolandscape studies, particularly in areas where the coast is fronted by islands, since the separation of islands from the mainland drives important ecological and sociocultural outcomes. This program creates accurate time-slice reconstructions of shoreline positions and palaeolandscapes when the user provides two components: 1) a digital elevation model of the target region (including currently submerged areas), and 2) a simple spreadsheet of relative sea-level elevations at different dates derived either from a glacio isostatic adjustment model of relative sea-level change, or from observed past sea-level data points. The tool is presented using the eastern coast of the Adriatic Sea in the Mediterranean as a test case, since this region has a complex coastline articulation due to combined geological and geomorphological factors. In this area, like in many other Mediterranean coastal areas, the separation of islands from the mainland following the last glacial maximum and throughout the Holocene has occurred in connection with important phases of the development, particularly of Mesolithic and Neolithic cultures, influencing human migrations and the spread of seafaring techniques. Reliable palaeolandscape reconstructions at different time slices are thus crucial for supporting archaeological interpretation. Flexibile and user-friendly, SeeLevelViz can compliment reconstructions of coastal landscape changes either based on glacial isostatic adjustment models or on relative palaeo-sea- level evidence, since simple, interactive visualizations are a powerful technique for understanding spatial time-series data, both for the interpretation phase of research, and for presentation to colleagues and the public. The program can be modified or used freely for papers, presentations, etc. by crediting and citing this article.

Keywords: Interactive visualization; Python; Coastline; Palaeogeography; Adriatic Sea

1. Introduction

1.1 Purpose and goals

This paper introduces a simple, interactive way for sea-level scientists to view and share palaeo sea-level reconstructions using only a spreadsheet of observed or modelled past relative sea-level (RSL) elevations, and a digital elevation model in TIFF format, either created by the user or retrieved from existing studies or open-source data repositories. It can also be used for sharing future sea-level change predictions if significant morphological changes during the proposed time-slices are not a factor. We suggest this method of presenting results since it is specifically created for the sea-level community and is simpler and more interactive for the end-user than using GIS or other programs to generate multiple iterations of static visuals. As an example use case, we share a DEM and sea-level reconstruction from an existing study (Dean et al., 2020) concerning the Croatian island of Korčula in the Eastern Adriatic, where dramatic relief above the 100 m isobath resulted in significant palaeolandscape change after deglaciation. This introduction section briefly discusses the general context of Pleistocene- Holocene modern RSL change that creates the need for sea-level visualizations. It also summarizes the use of observational or glacial isostatic adjustment (GIA) model reconstructions, and gives a brief regional context of the example case from Korčula in the Eastern Adriatic.

1.2. Pleistocene-Holocene Sea-level Rise

More than 120 m of sea-level rise has been reported globally in records like Barbados Corals (Fairbanks, 1989; Peltier and Fairbanks, 2006) since the last glacial maximum (LGM) which has resulted in significant palaeolandscape and environmental changes for coastal and shallow-shelf areas. Around the world, the sea-level research community has created reconstructions based on a number of morphological, archaeological, and biological proxies collected into datasets (Gehrels et al., 2011; Khan et al., 2019) which testify to the sometimes dramatic nature of these changes.

Since observational sea-level data are not homogenously preserved in all regions, and because RSL itself is different spatially due to the earth's response to changes in water and glacial loading, models of the GIA effect are also a large part of sea-level reconstructions since the last glacial maximum- e.g. (Lambeck and Purcell, 2005; Lambeck et al., 2014; Peltier et al., 2015), realized in computer programs e.g. (Spada and Melini, 2019b) using a variety of parameters, and often visualized against observed data when available e.g. (Vacchi et al., 2018). The large amount of modelled and observed data attest the frequency of palaeolandscape and shoreline changes in the Holocene, which can be discussed in terms of their effects on human and faunal populations (Foglini et al., 2016). As a result, there is a wealth of possible areas where dynamic visualizations of landscape changes can provide aid to interpretation and dissemination of scientific data to complement the widespread existing use of static visuals in this field.

1.3. Korčula Island and the Eastern Adriatic

As a test case for illustrating the value of dynamic visualizations of sea-level change, a ca. 6,000 km2 area was selected, located in the Mediterranean Basin, by the eastern coast of the Adriatic Sea (Figure 1). Geologically the area is part of the Adria Plate (Sani et al., 2016), including the relief of the westernmost Dinarids (Korbar, 2009) and the facing continental shelf up to the depth of ca. 120 m. The Dinaric mountain range is mostly shaped in Mesozoic-Triassic limestones and dolomites, with a minor extent of Eocene flysch terrains. A major thrust front, NE-SW oriented (Vlahović et al., 2005), controls the morphostructural setting of the eastern Adriatic coast, that is shaped in the form of ridges and depressions parallel to the thrust orientation. In the northern and central part, the region called Dalmatia, the relief results in a great number of islands separated from the mainland by the postglacial sea-level rise. Our study area is located in Central Dalmatia, where the islands are rotated counterclockwise with reference to the Dinaric strike. In the middle of the study area is the Croatian island of Korčula, separated by a shallow strait from the seaward protruding Pelješac Peninsula, and surrounded by other major islands (Figure 1). Korčula is an elongated island, with an area of 279 km2 and a hilly relief peaking in the central part at 569 m asl. The Island landscape is dominated by karst action, resulting in alternating smooth peaks and wide depressions, mainly poljes (Dean et al., 2020a) with no significant surface drainage. Outstanding prehistoric archaeological heritage is present on the Island, in the form of hill forts, burial mounds (Radić, 1999) and especially caves preserving archaeological sequences, among which is Vela Spila, where the stratigraphy ranges from the Late Upper Palaeolithic up to the Bronze Age (See Branscombe et al. (2020) and references therein). In

Korčula changing coastal landscapes and insularity proved to be relevant factors driving human settlement patterns (Dean et al., 2020); this is an example of how palaeolandscape reconstructions at different time slices are important for supporting archaeological interpretation in the area. Bathymetry suggests that in sea-level lowstands the islands around Korčula were connected by a very flat plain below the present-day isobath of – 70 m (Dean et al., 2020). Dramatic landscape changes have thus accompanied the inhabitants of this area since the Late Upper Palaeolithic, even at the scale of human life. Moreover, in this area present-day sea-bottom morphology closely resembles postglacial terrestrial landforms (Pikelj and Juračić, 2013) owing to the very low sedimentation rate (Giglio et al., 2020) caused by the poor sediment discharge of the rivers flowing through the few karstic valleys the estuaries which open in the mainland coastline (Felja and Juračić, 2018).

1.4. Interactive Visualizations

Interactive visualizations are a way for scientists to interpret and share scientific data using computer graphics. The main characteristics of interactive visualization in this program are the ability for the viewer to change things about the visualization, and for the visual to update quickly in response to the user's input. However, this principle can be applied to many other types of visualization, for example 2d plots or graphs, and users may be allowed to change the limits of the y or x axis and see the graph redrawn in real time, or to change the data series represented by the points. The main purpose of these capabilities is to help the scientist (initially) and later the audience of the scientific data (subsequently) view and search for different patterns in the data or derived statistical analyses, and to suggest additional statistical analyses to be performed (Buja et al., 1996). This represents a very important part of the scientific process, and though this phase of data exploration can be undertaken manually with excel or programmatically if using data-science platforms such as R or MATLAB, this is a time consuming and less responsive process (Sievert, 2019a) than a plot which can be updated simply by manipulating user interface elements such as buttons or sliders. Moreover, research has also shown that interactivity in graphics can help the audience understand scientific data more easily (Hood et al., 2020). Given this context, and the compelling nature of interactive visualizations, the RSL community should also attempt to make use of these technologies by deploying them in an easy to use program.

1.5. Python as a data science platform

Python is a programming language which can be used for data-science and creating graphical user interfaces (Python Team, 2020). It is also developed in an open-source context, meaning it is free and the underlying code is transparent and may be viewed by anyone (Python Team, 2020). Python has become very popular with scientists in recent years, thanks in part to configurations such as Anaconda (Anaconda Team, 2021) which make installation of the core functionality and additional modules easier. For science and engineering alone, more than 10,000 of these additional code modules (known as packages) written by other scientists and programmers are freely available online through package management programs like Pip (Pip Team, 2021) or through Anaconda for very specific scientific purposes and sub-fields. A Scopus search of abstract texts in the earth and planetary sciences fields using the search terms “ABS (python) SUBJAREA (eart)” yields more than 1,300 documents in the last ten years, with an exponential increase over time (see Figure 2). Given the widespread use of this platform, the sea-level community may also benefit from using and modifying a visualization program using this technology.

2. Methods

2.1. Program Dependencies

SeeLevelViz has been designed using Python. Qt (The Qt Company, 2020), which is a set of cross-platform software tools, is used to create cross-platform programs and graphical user interface elements such as those used to control the visualization. MayaVi (MayaVi Team, 2021), a scientific data visualizer for Python, is used for the 3D effects. The command pip freeze is used to freeze updating of all required packages to avoid incompatibilities due to version upgrades. The main external dependencies needed are python3 & pip3, pyqt5 & qt5, VTK, gdal. A number of other dependencies are also required; a full list can be viewed in the requirements.txt at the GitHub repository https://github.com/dsilas/SeeLevelViz. The other dependencies can then be installed using the following command:

```
pip3 install -r requirements.txt
```

2.2. Standalone usability

Normally, getting the SeeLevelViz program to run would require considerable technical expertise to install python and also install/manage of all the dependencies on the part of the end user, which is particularly complex on Windows computers. To make this step unnecessary, we package the program and all the dependencies as a standalone executable (.exe on windows, .app on Mac) using PyInstaller (PyInstaller Team, 2021), a bundling package for Python that is capable of loading an external spreadsheet and DEM. For the initial release we provide standalone Windows executable. We recommend that any future forks or contributions of the project attempt to create these standalone executable since providing these removes a serious obstacle to using the program. One unfortunate byproduct of this approach is that the stand-alone files are quite large (hundreds of megabytes) since they have to include all the software dependencies necessary to make the python program run. However, most universities now have high-bandwidth connections now, which mitigates this somewhat. Currently, binary builds are available for Linux and Windows. It is hoped that a Mac OS release will be created later. Any interested researcher with access to a late-model Mac computer and development tools is invited to assist with this process.

More information about running and building from source is available on the GitHub https://github.com/dsilas/SeeLevelViz.

3. Results

3.1 Initial release features

The initial release of the SeeLevelViz program focuses on a core set of basic features essential to achieve interactive RSL change visualizations. Presently, this consists of a graphical interface to prompt the user to select a DEM and a simple 2 column spreadsheet of RSL reconstructions: dates and elevations. The program renders the DEM, and draws a plane for the sea level. The interface allow the user to switch between sequential RSL data points and view the reconstruction. The user may alter the perspective of the 3D view by dragging the scene with their mouse, and a button to reset the view to the default is present in case of disorientation. An interface element exists which also allows the user to exaggerate the Z elevation of the rendering, since DEMS that cover a large area may not be informative without considerable z-axis exaggeration. From a button in the top of the window, the program can also export a static image of the current 3d visualization in standard formats for use in print journals or conference presentations.

3.2 Installing and using SeeLevelViz

We recommend for researchers on computers with Windows or Linux distributions who wish to use the program as-is to simply download the stand-alone implementation from the GitHub repository in the“releases” section or the Mendeley data repository supplement linked to this paper, then follow the steps in 3.3 below to use the program with their own data. This should be all that is required.

For advanced users who wish to recreate or modify the SeeLevelViz program themselves, the code repository of the program can be found at https://github.com/dsilas/SeeLevelViz where it can be forked, issues can be posted, etc. The GitHub repository contains a list of all required software at SeeLevelViz/requirements.txt, but the main requirements are python3, pip3, qt5, VTK, and gdal as stated above.

3.3 Data preparation

To use the program with their own data, the researcher must prepare two files: A digital elevation map of the area of study, and a two-column csv spreadsheet. Details for preparing these files are given below.

3.3.1. Digital elevation map

The digital elevation map should be a geoTIFF of the area of interest. Z values can be either in meters or feet, but you must use the same system of measurement in the spreadsheet. The projection of the geoTIFF is not relavent as the 3d visualization is not georeferenced. You can use a GIS program like the free QGIS, or ArcGIS to create a geoTIFF. The source or sources of the elevations in the DEM are of course up to the user – bathymetric soundings, LIDAR, interpolation from contour lines, etc. The example DEM of the Korčula island from Dean et al. (2020) area is an interpolation combining bathymetric soundings and satellite datasets. Dean et al. (2020) also describes one method to create a DEM by merging free datasets in QGIS.

3.3.2. Spreadsheet of RSL reconstructions

The simple spreadsheet must be saved as a csv (comma separated value) file, not an excel spreadsheet. This can be done in excel by choosing "Save as" and choosing "Comma Separated Values" for the format. The spreadsheet must consist of only two columns with the text values in the first rows of dateBP and elevation. dateBP contains years before present (BP). elevation contains the reconstructed RSL for that year, relative to present sea level. Researchers in countries where data products are released using imperial units, take note: The distance/elevation units of your DEM must be the same as the elevation units in your RSL spreadsheet – the SeeLevelViz program does not perform any check for this. The example spreadsheet is available at the GitHub repository SeeLevelViz/data/input.csv

4. Discussion

4.1 Value of interactive visualizations for RSL studies

The field of sea-level studies can benefit significantly from a simple, interactive, and open-source visualization tool for reconstructions of RSL. The typical interpretive work flow of a sea-level scientist doing landscape reconstructions in the past or future might consist of something like the below list. The below process is not dissimilar from that used by scientists in many other fields as discussed by Sievert (2019b).

1. Obtain observational or modelled data points that reconstruct relative-sea level in the future or past. See section 1.2)

2. Obtain a digital elevation map from public or private repositories of global sub-sea and emerged elevation data e.g. (GEBCO, 2014; Tozer et al., 2019) or new local remote sensing data e.g. (Foglini et al., 2016). In order to get a reliable result it is necessary to correct the topographic/bathimetric DEM

taking into account as accurately as possible all changes in the topography of the area since the time-slice in question, such as sediment deposition and erosion processes. It may also be necessary to correct the DEM elevations in order to account for the overburden due to sediments accumulation which, especially on the inner shelf, can be relevant. For an example approach to this see Lo Presti et al. (2019).

3. Collation between the DEM obtained in step 2 and elevations obtained in step 1 to recreate landscapes, coastlines etc at relevant time slices by repeated and iterative comparison between spreadsheets, GIS layers, model outputs, etc.

4. Interpret the effects of palaeolandscape change with results obtained in step 3 in terms of likely impact on subject of research- such as geomorphogical processes, environmental change, human societies, faunal dispersion, etc.

5. Share results in the form of static graphics in publications or presentations e.g. Figure 3.

The interactive visualization program SeeLevelViz introduced in this research aims to make steps three & four easier. Usually these steps require time consuming and slow interactions. For example, a GIS program can be used to create a cover at an arbitrary sea-level specified by the user, but this requires several steps of user interaction, in addition to fluency with GIS programs, and the need to continually cross reference the spreadsheet of sea-level reconstruction data points, or use advanced scripting to automate the process. Likewise, a program like SELEN4 (Spada and Melini, 2019b) can be used to re-run the model at different time slices; however this requires a higher level of technological skills, and in both cases the process is not immediately responsive or interactive. The higher technical expertise required for the above solutions also decreases the access to it among geoscientists. The program developed here is an excellent tool for viewing sea-level data in terms of palaeolandscape changes during the data interpretation phase because it responds immediately to the input of the user for changing the time slice, and can be rotated in real time in three dimensions to aid the scientist in visualization as a supplement to other tools such as sophisticated an GIS analyses and GIA models. It also provides a simple way for the researcher to interact with GIA modelled or observational RSL data.

In addition, the SeeLevelViz program has value for step 5 – sharing the palaeolandscape implications of RSL change with other members of the community. Typically this is done with static visuals that show only the reconstruction at a very limited number of time slices (e.g. Figure 3), those deemed most relavent to the research question, and shared in the context of journal articles or conference presentation slides. The dynamic visualization of this program promotes the sharing of open, reproducible data in the form of digital elevation maps and spreadsheets of RSL reconstruction needed to make the program work, and it allows colleagues to easily view reconstructions in three dimensions at whatever time slice available data permits in order to assess and expand interpretations.

4.2. Best practices for use

The SeeLevelViz program works best with a sequence of data points that indicate a clear trend to sea-level change, rather than data points which contradict each other. The latter situation is often the reality in many localities when actual observational data is relied upon. For example, the dataset of Israeli sea-level indicators (Dean et al., 2019) in Figure 4 would present a confusing and non-linear reconstruction if fed directly into the program as a two column spreadsheet, because there are multiple datapoints on the same date, or datapoints which reverse the trend of those most temporally proximal. A more suitable dataset for use with this program would be a spreadsheet-based output of a regression analysis, for example the error-in-variables IGP regression shown in the same figure, which reduces "noise" to an overall trend.

GIA model outputs such as those generated by SELEN4 (Spada and Melini, 2019b) are also an excellent dataset to use with this program for the same reason. It is important to note, however, that the

RSL variations induced by GIA are not spatially uniform and characterised by a marked regional imprint caused by the interactions within the solid earth-oceans-cryosphere system (Spada and Melini, 2019a). For this reason, if the researcher intends to visualize large areas (hundreds of kilometres or more of latitude/longitude) using this program, it is highly recommended to first use SELEN4 (Spada and Melini, 2019b) or another GIA modelling solution across the study area before SeeLevelViz is used, to ensure that RSL over the visualized areas was actually uniform during the selected time slices.

In addition, it bears noting researchers must use the program only for visualizations of past sea levels in study areas where sedimentation, erosion, and other geomorphological processes have not significantly changed the nature.

4.3. Additional features for further development

A number of possible additional features were not added to the initial release. However due to the open source nature of the SeeLevelViz program, other RSL researchers with the necessary technical capacities with Python and GitHub can either create a fork of the repository, or submit code to this repository for approval according to the normal GitHub procedures.

One such possible feature is smooth interpolation of sea levels between data points, via an interface element. We currently have avoided implementing this because it can create the impression of data points which do not in fact exist, and because the interpolation itself can be a complex statistical process. However, such a feature may be desirable to some users for cosmetic reasons for presentation purposes

Another area that the program does not currently treat with are the 2 σ uncertainties typically associated with sea-level data – either chronological (for example 14C date 2 σ) or in the elevation levels of observed data points using concepts such as indicative range, or modelled reconstructions with 2 σ or other uncertainty envelopes. This possibly could perhaps be added by the use of transparent additional sea-level cover layers at the levels of the uncertainties.

The ability to easily switch between alternative datasets (such as different GIA models) for the same site is also a potentially desirable feature, which could use either an interface button to fluidly switch between models, or transparent layers as described above.

The ability to host the interactive visualization on a website so that any internet-connected individual can access the visualization using a web browser is also an extremely desirable feature. Currently this has not been pursued due to the cost and complexity of reliable web hosting and technical challenges in getting the required libraries to perform well.

Additional cosmetic features suggest themselves as well. For example a contour line marking the present day sea-level "0" is also advisable for future implementation, as are other potential graphical options like contour lines at set isobaths, and additional texturing options for the 3D DEM.

5. Conclusion

The SeeLevelViz program is a simple, free, and open-source tool to visualize and "play with" the palaeolandscape implications of sea-level changes from observational datapoints or GIA models. This allows the researcher to consider the changes in their study area over time in a flexible way that can help guide the interpretation phase and suggest additional, more formal terrain analyses to produce conclusions about a range of topics such as coastal morphology and dynamics, palaeolandscape change, faunal dispersion over time, and impacts on ancient (or future) human societies.

In addition, the tool can be an eye-catching and memorable way to present results to other researchers, either in-person at conferences, or by distributing the app with your own map and spreadsheet of sea-level reconstructions.

Author contributions

All authors contributed to the general discussion of the topics addressed, In particular SD and MP have been in charge of the article design and writing, GS provided the GIA models realizations and checked the consistency of the program outputs, SB designed the program using Python.

Data availability

The program can be downloaded from the Mendeley data repository associated with this article in a version made at the initial release of the paper. The latest release can be downloaded from the GitHub page https://github.com/dsilas/SeeLevelViz in the releases section. For advanced users wishing to build and modify the program, the code is also available at the GitHub.

Declaration of competing interest

The authors declare no conflicts of interest.

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Figure Captions

Figure 1. Regional setting of Korčula Island, taken from (Dean et al., 2020); top: general view of the Adriatic Sea (the red rectangle identifies the area for which the dynamic visualization is provided, the red dot indicates the location of Vela Spila cave); bottom: Korčula and surrounding area. Tectonic information: (Korbar, 2009; Surić et al., 2014). Map and relief data:(GEBCO, 2014; GADM, n.d.).

Figure 2. Number of articles in Earth and Planetary science fields with abstracts containing the word python from 2010-2020. Generated by scopus.com

Figure 3. Example of a typical static sea-level reconstruction visual, reprinted from (Dean et al., 2020). This visual was created with QGIS (QGIS Team, 2021) using sea-level reconstruction data points obtained by SELEN[4] (Spada and Melini, 2019b). The DEM is a combination of public sources and created for (Dean et al., 2020); see references therein for additional details and sources.

Figure 4. Example of observational RSL dataset reprinted from Dean et al. (2019) figure 5. The observed RSL data points (circles and diamonds) do not always indicate a clear, non-contradictory trend until subjected to an error-in-vari*ables IGP regression.*

Fig. 1

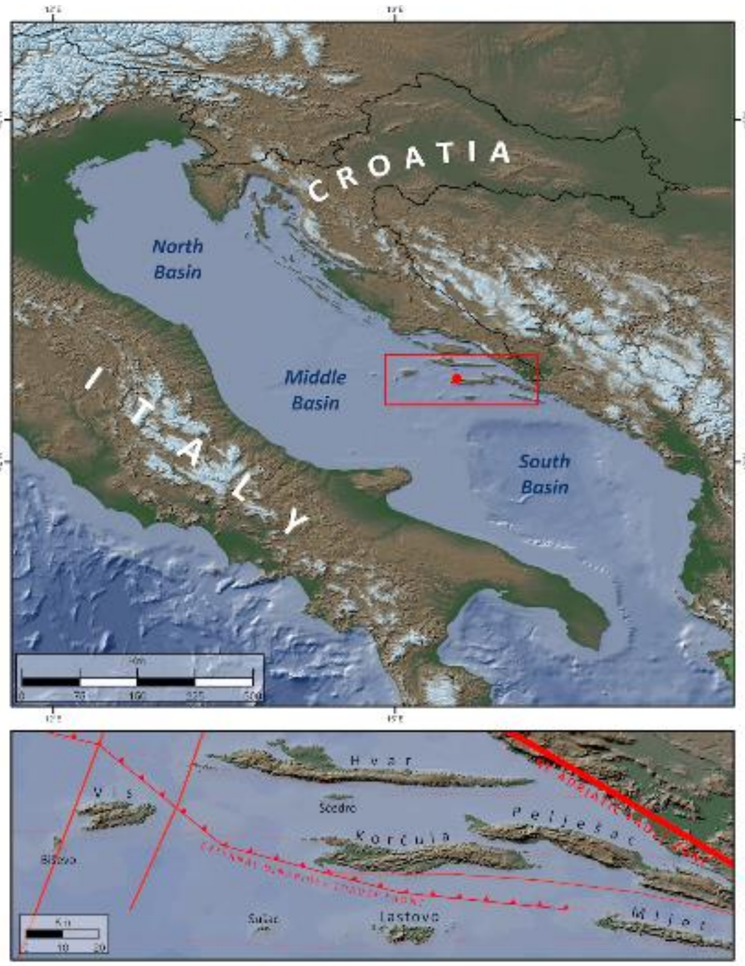
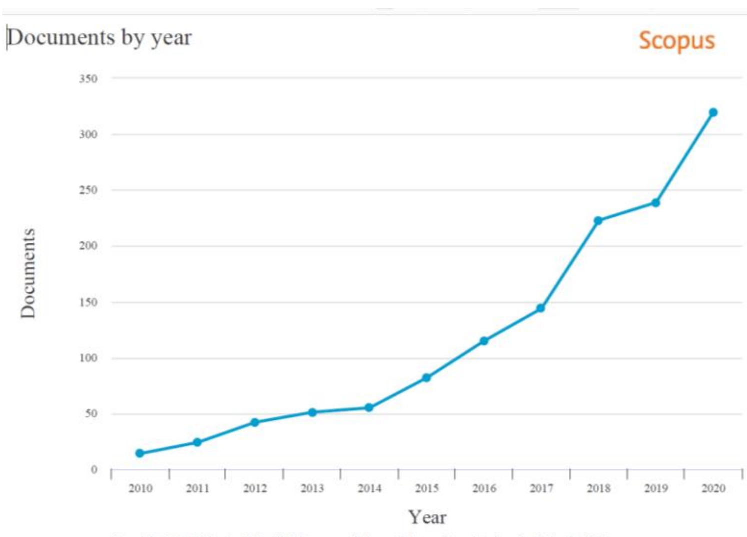

CROATIA
North Basin
Middle Basin
South Basin
ITALY
Hvar
Vis
Korčula
Pelješac
Lastovo
Mljet

Fig. 2


Documents by year
Scopus
350
300
250
200
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Documents
2010
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Year
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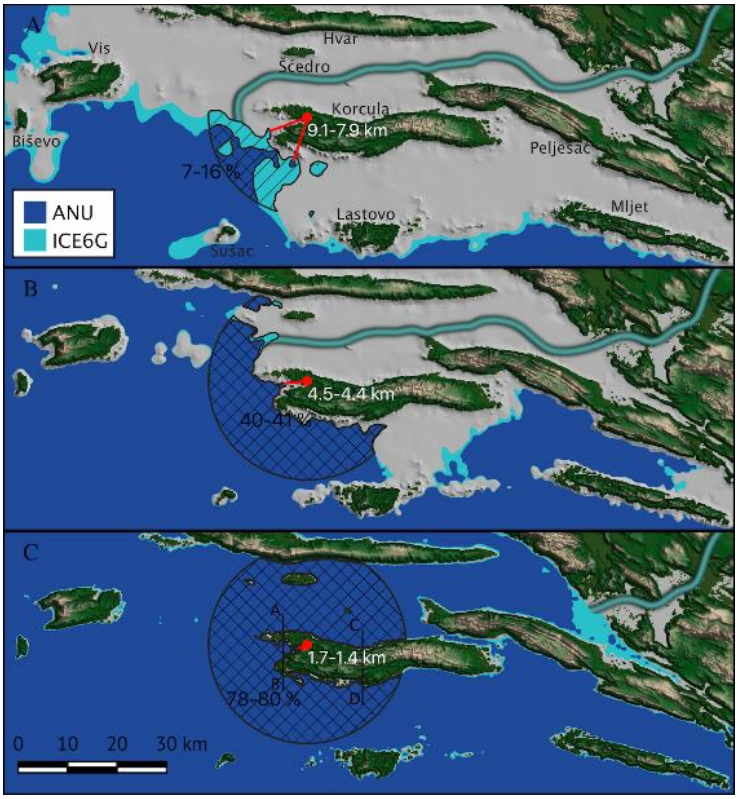
Fig. 3


A
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Susac
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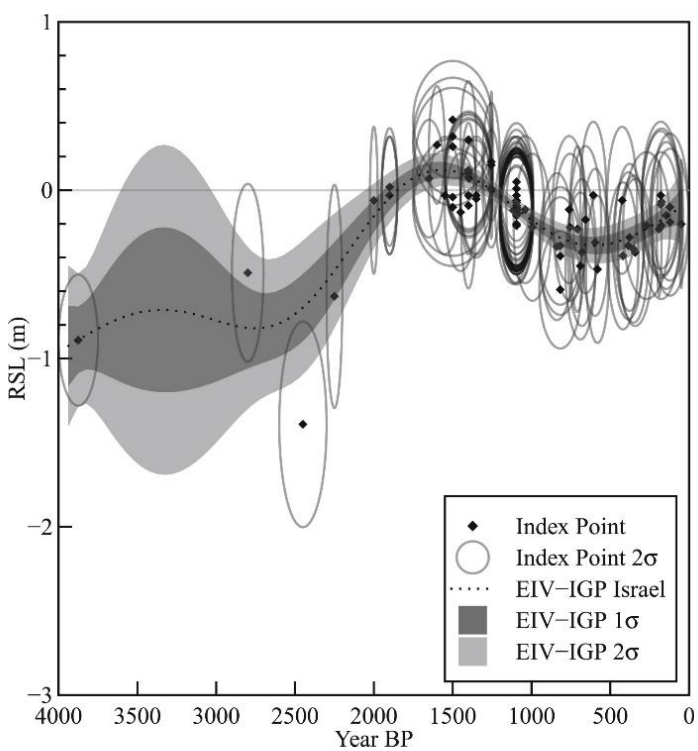
Fig. 4


RSL (m)
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3500
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Year BP
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EIV−IGP Israel
EIV−IGP 1σ
EIV−IGP 2σ