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A generalised approach to reconstructing geographical boundary conditions for palaeoclimate modelling

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Studies on the palaeoclimate and palaeoceanography using numerical model simulations may be considerably dependent on the implemented geographical reconstruction. Because building the palaeogeographic datasets for these models is often a time-consuming and elaborate exercise, palaeoclimate models frequently use reconstructions in which the latest state-of-the-art of plate tectonic reconstructions, palaeotopography and -bathymetry, or vegetation have not yet been incorporated. In this paper, we therefore provide a new method to efficiently generate global geographical reconstructions that are suitable for palaeoclimate modelling. We use a plate-tectonic model to make global masks containing the distribution of land, continental shelves, shallow basins and deep ocean. The use of depth–age relationships for oceanic crust together with adjusted present-day topography gives a first estimate of the global geography at a chosen time frame. This estimate subsequently needs manual editing of areas where existing geological data indicates that the altimetry has changed significantly over time. Certain generic changes (e.g. lowering mountain ranges) can be made relatively easily by defining a set of masks while other features may require a more specific treatment. Since the discussion regarding many of these regions is still ongoing, it is crucial to make it easy for changes to be incorporated without having to redo the entire procedure. In this manner, a complete reconstruction can be made that suffices as a boundary condition for numerical models with a limited effort. This facilitates the interaction between experts in geology and palaeoclimate modelling, keeping the reconstructions up to date and improving the consistency between different studies. Moreover, it facilitates model inter-comparison studies and sensitivity tests regarding certain geographical features as newly generated boundary conditions can be easily incorporated in different model simulations. An example is presented, covering a late Eocene reconstruction (38 Ma), a MatLab script used to perform the procedure is provided in the Supplement.

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1 Introduction

As the interest grows in assessing how the climate may change under increasing anthropogenic forcing, the field of climate modelling is steadily growing and improving. These models are mainly tested by making hindcasts of the present day and pre-industrial climate. Anthropogenic forcing may lead to future climate states that are beyond the range for which models can be validated with observations. Reconstructing the palaeoclimate may help to increase the confidence in predictions by simulating episodes in Earth's history with climatic conditions that were drastically different to that of today. While the number of measurements is generally much more limited than for the present day, a considerable amount of proxies is available to constrain the conditions of several such periods (e.g. the Paleocene–Eocene thermal maximum, Mid-Eocene climatic optimum, Eocene–Oligocene transition, Oligocene–Miocene Boundary and Eemian). The equable climate problem (Huber and Caballero, 2011) is one nice example showing that models may still be lacking some essential dynamics to explain how the meridional atmospheric (or sea surface; Biji et al., 2009) temperature gradient can become so small in a greenhouse climate. It is therefore essential to try and simulate the past climate with a similar amount of detail as is done for the present to really expand our understanding of the climate system when it is forced far beyond its present state.

Setting appropriate boundary conditions for deep time palaeoclimate simulations is challenging, as these are often poorly constrained. Next to the atmospheric composition, solar insolation and land surface properties, the global geography can also be of great importance (Barron and Washington, 1984). The breakup and collision of continents likely caused major climate transitions in the past. For example, the India–Eurasia collision caused a large scale uplift that resulted in regional climate changes but also affected the global circulation and hydrological cycle (Ramstein et al., 1997; Dupont-Nivet et al., 2007, 2008; Caves et al., 2014). Furthermore, the opening of ocean gateways such as the Tasman Gateway impacted the ocean circulation and thus the

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redistribution of heat, resulting in both changed surface and deep ocean temperatures (Bijl et al., 2013; Sijp et al., 2014). Many of these themes are subject of ongoing studies and the continuous acquisition of new data, either of palaeo-altimetry/bathymetry or from tectonic reconstructions. It is therefore crucial that new relevant insights can be incorporated easily and swiftly in boundary conditions used for palaeoclimate modelling.

Implementing different geographies is not without issues; the increasing but limited model resolution obscures certain potentially critical features (such as narrow ridges, mountain ranges and straits) and may require some additional manual changes. Additionally, plate-tectonic reconstructions have their own uncertainties and are continuously being expanded and improved. This causes large discrepancies between model simulations because different studies use reconstructions of varying age and approach. A simple but striking example is given by Gasson et al. (2014), who used the output of several coupled global atmosphere–ocean models to force an ice sheet model simulating the Antarctic glaciation during the Eocene–Oligocene transition (~ 34 Ma). Their main conclusion states that it is almost impossible to determine the CO₂ threshold for the inception of ice since the models use such different topographies. Geographical reconstructions used in palaeoclimate modelling are often based on older reconstructions that are adjusted for a specific case. These reconstructions may thus be based partially on information that is outdated and are usually only made for a specific set of time frames, which greatly limits their application in other studies. Additionally, developments in coding and computer hardware allow for model simulations with a significantly higher resolution that in turn require more detailed boundary conditions.

This calls for a new approach where the latest geological reconstructions can directly be incorporated together with improving constraints on palaeoaltimetry (e.g. Dupont-Nivet et al., 2008) and translated into a gridded topography and bathymetry map. In this paper, a method is presented that allows for the creation of geographical reconstructions based on the most recent geological insights with relative ease. The various

steps and methods are demonstrated through a specific example for the late Eocene (38 Ma).

2 Plate tectonic reconstruction

The backbone of our method is a plate-tectonic model that provides a first-order reconstruction of palaeogeography for the Phanerozoic (Seton et al., 2012). This model is provided in the free plate reconstruction software GPlates (www.gplates.org, Boyden et al., 2011), which is widely used in tectonic research. The reconstruction of Seton et al. (2012) serves as a basis, and can be updated when new reconstructions become available. Because we aim to study palaeoclimate, we place our reconstruction in a palaeomagnetic reference frame (Torsvik et al., 2008; Hinsbergen et al., 2015). Starting from the present-day topography, the outlines of land, continental shelves and shallower regions such as intra-oceanic ridges and plateaus are defined. Using the reconstruction model, these features are then shifted towards their positions at a chosen time frame (here: 38 Ma) and exported as a png image (Fig. 1) to create a rectangular coloured grid with a sufficiently high resolution to satisfy the intended grid of the final reconstruction. The image can be imported by a computational program such as Mat-Lab for easy manipulation and conversion into a numerical grid. For its application as a climate model boundary condition, the final geographical reconstruction should be stored as a gridded (latitude–longitude) topography–bathymetry dataset. To start with, ocean bathymetry is estimated using the ocean floor age grid provided by Müller et al. (2008a) in combination with the plate tectonic model. The position and age of oceanic plates in the model is then translated into a bathymetry map using the general depth–age relationship for oceanic crust. Here, we use an average of the relations given for the main ocean basins (Atlantic, Pacific and Indian Ocean) treated by Crosby et al.

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time frame (Sømme et al., 2009). Since the late Eocene is a greenhouse climate, a flat and relatively shallow shelf is implemented here but this can easily be done differently for other periods.

The next, more challenging step is creating a realistic land topography for a chosen time frame. Good estimates of altimetry are only available for a limited number of locations and time intervals, making the reconstruction of palaeotopography a difficult task that requires a lot of manual input. For example, the global Eocene topography by Markwick (1998) is still used and referred to regularly in palaeoclimate modelling. Our approach here is to first consider the present day topography (using the ETOPO2v2 dataset, <http://www.ngdc.noaa.gov/mgg/global/relief/ETOPO2>) and adjust it to the 38 Ma configuration using the plate tectonic model and the land mask shown in Fig. 1. Later on, specific topographical features can be corrected manually, depending on the specific demands of the application and the amount of information that is available. The resulting first stage of the reconstruction is given in Fig. 2.

3 Generic adjustments

The geography obtained at this stage (Fig. 2) is not yet accurate and contains a number of gaps that remain to be filled (mainly collision zones and transition regions between continental and oceanic crust). Especially the land topography needs to be adjusted so that it better matches palaeoaltimetry estimates for the considered time frame. Although glaciers possibly existed on Antarctica (Scher et al., 2014) and Greenland (Eldrett et al., 2007), the presence of continental-scale ice sheets in the Eocene is unlikely (Deconto et al., 2008). Therefore, to correct for the effect of isostasy the present-day bedrock topography is raised by 1/3 of the current ice thickness. The changes mainly affect Greenland and Antarctica, although for the time window chosen in our example a highly detailed palaeotopography of Antarctica is made by Wilson et al. (2012). The latter, however, assumes the Antarctic continent to be at its present-day location which does not fit into our reconstruction. Similar to how the topography was treated

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above, the reconstructed Antarctic palaeotopography is fixed to the plates defined in the plate-tectonic model and adjusted towards its 38 Ma configuration. In practice, only the area a.s.l. is incorporated in the reconstruction and combined with the previously determined bathymetry. This is done to avoid possible discrepancies between regions of the ocean floor that are reconstructed using different methods.

Although most of the ocean floor has been reconstructed, a large gap is still present in the Neotethyan region between Africa, Eurasia, India and Indochina. While in the circum-Pacific area the crust lost to subduction was entirely oceanic, the former was characterised by multiple continental collision and subduction episodes (Stampfli and Borel, 2002). The Neotethys is introduced manually, based on the incorporation of GPlates reconstructions covering the Mediterranean region by Van Hinsbergen et al. (2012, 2014), the Arabia–Eurasia collision zone by McQuarrie and Van Hinsbergen (2013), the Arabia–India plate boundary zone by Gaina et al. (2015) and the India–Asia collision zone by Van Hinsbergen et al. (2011, 2012). A deep ocean basin with a depth of 4500 m is assumed, which is close to the value used in Müller et al. (2008a), representing the Neotethys at 38 Ma.

Next, we adjust the elevation of several mountain ranges towards values that are more representative for the considered time frame. Since most of the current elevated regions underwent a considerable part of their uplift after the late Eocene (such as the Andes, Himalayas and East African Rift) they will have to be lowered, while eroded regions may require some uplifting (for instance large river catchments). More specific changes for the example considered here will be discussed in more detail in Sect. 4, the result of the generic changes is first shown Fig. 3.

4 Specific adjustments for the late Eocene

The example shown thus far is largely representative for the late Eocene (38 Ma) geology, but now a number of time-frame specific adjustments are made that have not yet been treated in the previous sections. Several major tectonic events took place

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prior to and during the Eocene–Oligocene transition that had an impact on the global climate. A brief overview of these events and how their potential impacts are implemented specifically is given below and a map of the masks used to apply the various changes is provided in Fig. 4. The combined effect of these adjustments is indicated by the highlighted areas in Fig. 5, note that the effects of the land mask shown (in white) in Fig. 4 have not yet been implemented. The latter is used to correct the land boundaries after the manipulations discussed in Sect. 5.

The collision between Greater India and Eurasia is causing profound changes to the surrounding geography (Van Hinsbergen et al., 2012). The Neotethys Ocean narrows due to the combined northward propagation of Africa and India, leaving the Mediterranean Sea and the northern Indian Ocean. Further north, a major intra-continental seaway known as the Paratethys covered much of central Europe and a considerable part of western Asia. This was mainly a shallow basin except for the South Caspian and Black Sea areas, as it was mostly underlain by unextended continental crust. The extent of the Paratethys as well as the distribution of the surrounding continents is determined using the GPlates reconstructions mentioned in Sect. 3. The Neotethyan subduction-collision systems also create a large-scale uplift in southern Asia with primarily the formation of the Himalaya mountain range and the Tibetan Plateau. To the north and west, this uplift forces the westward retreat of the relatively shallow Paratethys leaving several isolated basins (Meulenkamp and Sissingh, 2003; Bosboom et al., 2014a). In addition, the formation of a rift between Antarctica and South America causes the opening of the Drake Passage with the first formation of oceanic crust at around 35 Ma (Livermore et al., 2005). A similar process is taking place south of Australia with the formation of the Tasmanian Gateway. While its opening already occurs around 50 Ma, the Tasmanian Gateway initially remains shallow. Coincident with the transition from a slip-boundary towards North–South spreading between Australia and East Antarctica (Bijl et al., 2013), a profound deepening phase occurs from 35.5 Ma onwards. The deepening and widening of the Tasmanian gateway is further complicated by a northward extension of the Antarctic shelf and an elevated Tasman Rise which

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both sank over time (Stickley et al., 2004; Close et al., 2009). Dependent on which absolute plate reconstruction frame is used, the opening of the Tasmanian Gateway can occur either to the north or south of 60° S paleolatitude. This can have important consequences for the direction of a possible initial throughflow and again stresses the importance of correct paleogeographies in paleoclimate modelling. The related northward motion of Australia combined with the rotation and rifting taking place around Indochina also causes a gradual blocking of the Indonesian Throughflow during the Oligocene (Hall, 2002).

As was pointed out before, some smaller geographical features have also been treated individually. Mountain ranges that are believed to have experienced major uplifts since the late Eocene are mainly the Andes, Himalayas, Sierra Nevada (USA), East African Rift and Middle East, which are all lowered significantly. The southern Tibetan Plateau was lowered more than the Himalayas since a narrow yet high ridge was already present while the adjacent plateau was still much lower (Van Hinsbergen et al., 2012). The northern part of the Tibetan Plateau is changed into lowland that surrounds the retreating Paratethys in the Tarim Basin (Dupont-Nivet et al., 2008; Bosboom et al., 2014b; Sobel et al., 2013). Related to the changes in Eurasia mentioned above, the narrow Tethys is drawn as a deep ocean while the Paratethys consists mainly of shallow seas with the Turgai Strait almost closed (Bosboom et al., 2014a). The latter forms the connection between the Arctic Ocean and the Paratethys and is an important contributor to the water budget in Central Asia. During the Early Eocene, the Arctic Ocean may have been completely isolated as indicated by freshening reported in Brinkhuis et al. (2006). No such events have been documented for the late Eocene so here we assumed several relatively narrow and shallow channels to be open. The western part of the Amazon basin was still flooded during the late Eocene (Hoorn et al., 2010). A kinematic reconstruction of the Caribbean region by Boschman et al. (2014) is adopted to treat the Panama Seaway. This gateway connecting the tropical Pacific with the Atlantic Ocean is still open but only with shallow waters (similar to the Indonesian Throughflow today), as it consists of an intra-oceanic volcanic arc since the late Creta-

time. For instance, river basins such as the Amazon, Rio de la Plata, Congo and Mississippi were just carved out deeper after the sea level dropped and other depressions were only created during glacial periods (e.g. the Great Lakes).

Finally, the application of the geographical reconstruction will usually be at a lower resolution than the one used until now (0.1°) and the high level of detail in the present-day topography may be misleading with respect to how precise palaeotopography is actually known. The last step is then to apply a squared smoothing mask, performing a 2-dimensional running mean with a 1° width for the example, of which the result is shown in Fig. 6. The mask size can be chosen differently and after smoothing, the global geography data is extrapolated onto the desired output grid (e.g., longitude–latitude) to be stored as a NetCDF file.

6 Conclusions

We have presented a new method to create global geographical reconstructions that can be used as boundary conditions in palaeoclimate model simulations. Starting from a plate-tectonic reconstruction, the depth of the ocean floor was estimated and combined with a reconfigured present day topography. An overview of the different steps making up the procedure is given in Fig. 7. Reconstructed plate trajectories, a background rotational frame and a set of boundary lines are fed into GPlates to make a global plate-tectonic reconstruction for a particular time frame. Within the same setup, present day topography and ocean floor data are manipulated and shifted to fit the same geographical configuration as the rest of the output. The latter is then used in a MatLab script together with some external input (mostly from literature) to create a global gridded altimetry–bathymetry dataset that is stored as a NetCDF file. This results in a highly detailed dataset that needs some time-specific changes, after which it is smoothed and extrapolated onto the desired computational grid.

Even though we performed a number of manual adjustments, interfacing GPlates with our MatLab script allows for the development of global geographical reconstruc-

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tions with limited effort. The primary focus was to use a plate tectonics model not originally designed to create numerical grids as output, that can be altered afterwards without having to run through the entire process again (only some of the masks may need to be redefined). Creating a new grid for a different point in time or a new configuration (e.g. using a different rotation framework) should allow the user to make multiple reconstructions in a few days' time. In case of a time slice experiment, one can also create appropriate boundary conditions for each time frame instead of making some minor adjustments to an average geography, to really try and catch the effect of gradual but global changes. The amount of manual handling depends on the demands of a specific application and can consequently be very limited but the procedure does not inhibit additional adjustments for further detail and correctness. In the example above, the output grid is defined as having a 0.1° resolution but can easily be extrapolated onto a coarser grid, which may require some more elaborate smoothing.

As the procedure starts from a plate tectonic model, most of the features important for modelling applications are quite realistic. The width and depth of ocean basins, presence of oceanic ridges and plateaus, position of continents and opening or closing of gateways are all directly incorporated in the final result. The set of boundaries shown in Fig. 1 are coupled to individual plates and can easily be linked to a different reconstruction framework. When comparing the result (Fig. 6) to other recent reconstructions used in palaeoclimate modelling, several differences quickly become evident. For instance, the global geography used in Ladant et al. (2014) is coarser and contains less detail in both land topography and ocean bathymetry. The Southern Ocean gateways are also much wider, which is probably a result of both the large grid spacing used for the climate model and the difference in time frame considered as this reconstruction is based on an Oligocene geography Lefebvre et al. (2012). Herold et al. (2014) have manually added a lot of detail to both the land surface and ocean floor in their reconstruction but here the problem remains that there can be considerable differences in continental positions as the geography is bound to a specific time frame. Details within

the contours of an older reconstruction can still be added but changing the relative positions of various land masses is not straightforward.

In summary, the reconstruction method presented here can provide detailed palaeogeographical datasets with relative ease for climate model studies and permits users to customise the result to their specific needs. This should facilitate the communication between geologists and climate modellers in their efforts to improve the quality and consistency of future palaeoclimate simulations.

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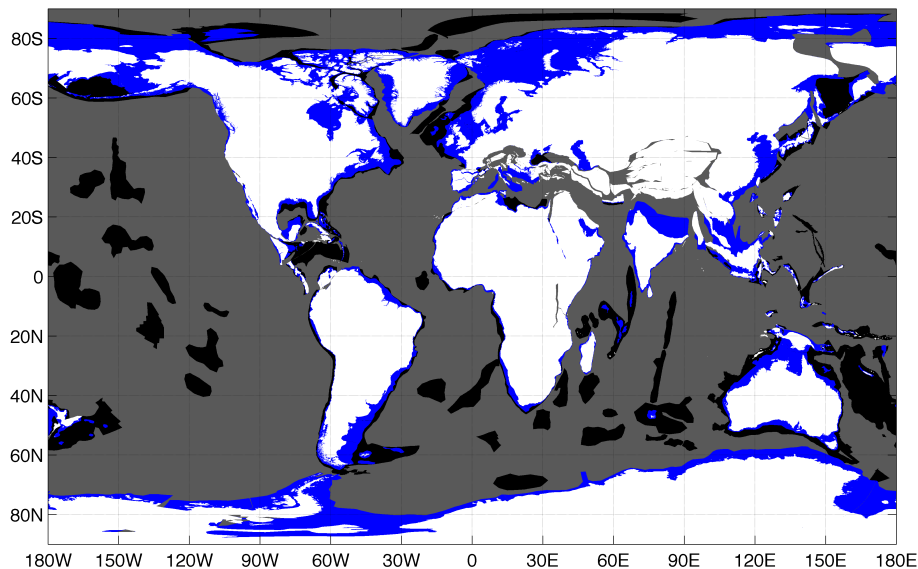


Figure 1. Earth reconstruction from the plate tectonic model at 38 Ma showing shifted present day land surface (white), continental shelves (blue) and relatively shallow ocean regions (black). Remaining in grey are then the deep ocean and zones that are yet unidentified in the plate-tectonic reconstruction model.

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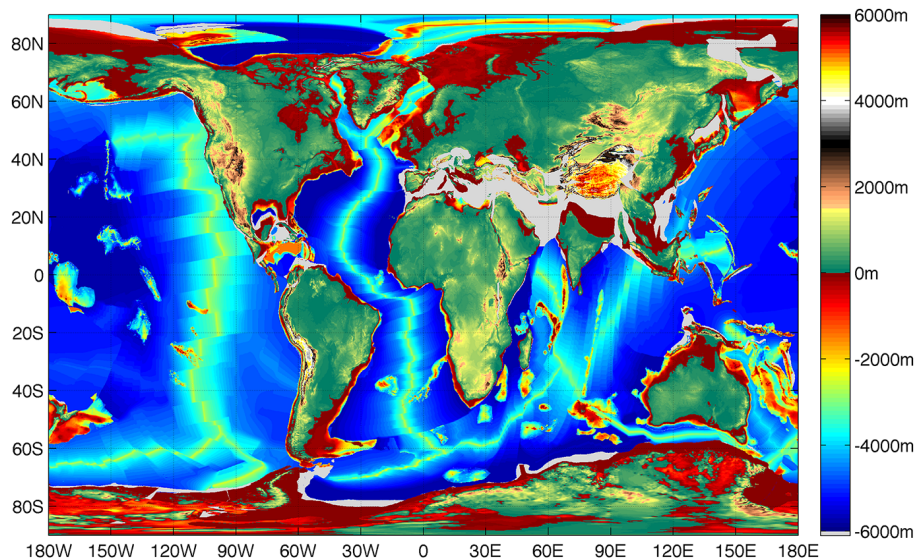


Figure 2. Reconstructed global geography at 38 Ma using the depth–age relationship, the Müller et al. (2008a) reconstruction, shallow basins, continental shelves and the present-day topography. The areas shaded in light grey are gaps which still have to be addressed.

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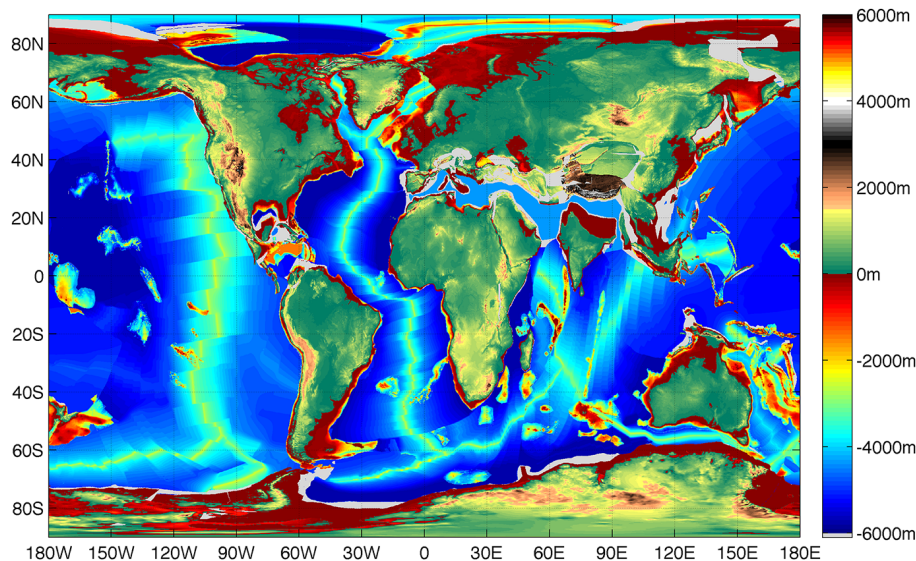


Figure 3. Reconstructed topography and bathymetry with adjustments to polar regions and a lowering of several mountain ranges. Changes can be noted mainly in Greenland, Antarctica, the Neotethys Ocean, the Andes and the Himalayas.

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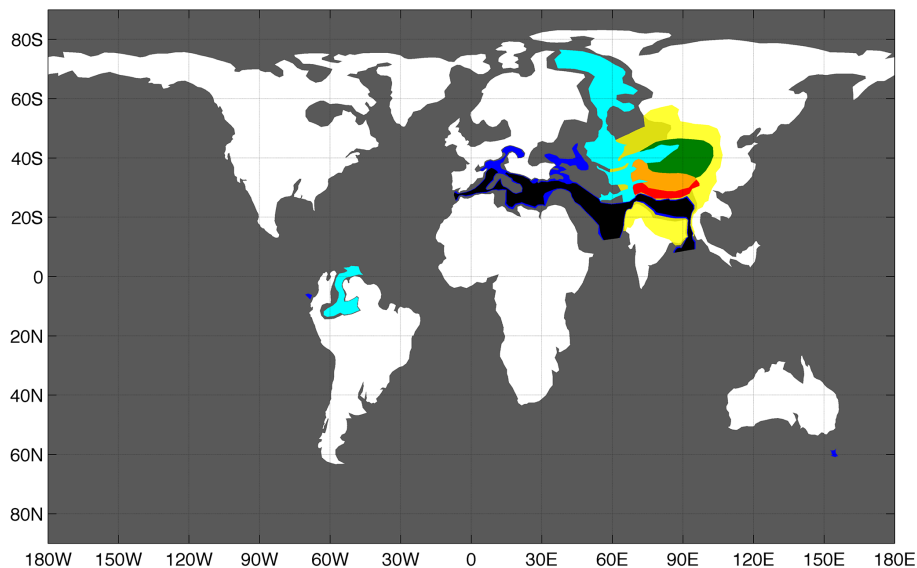


Figure 4. Masks used for manipulation of the reconstruction; white represents land, cyan shallow water, blue sea and black ocean. In southern Asia, green, yellow, orange and red indicate areas that are lowered manually by different ratios.

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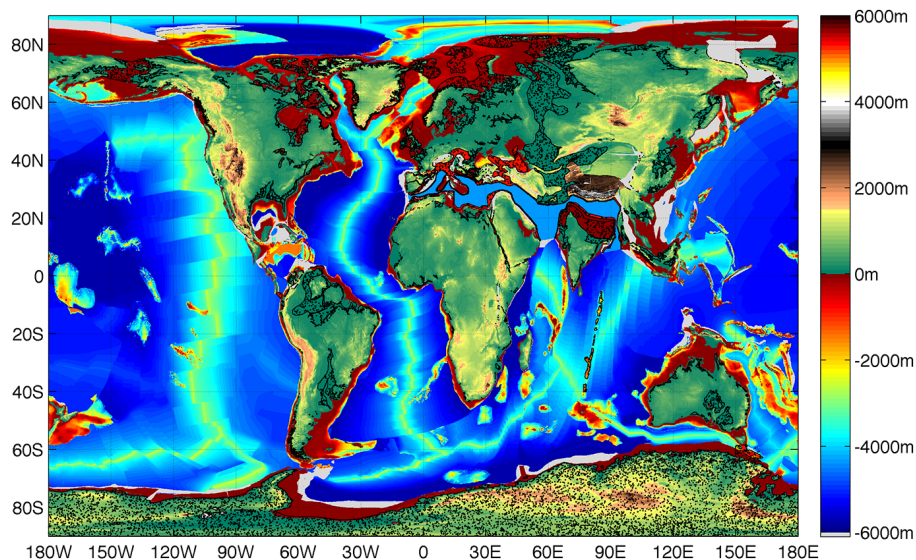


Figure 5. Reconstructed topography and bathymetry with specific adjustments indicated by black dotted areas, these include mainly Antarctica, southern Panama, the Amazon and several other river basins, the Hudson Bay and Great Lakes, Tethys and Paratethys, the Ninety-East Ridge and the Tasman Rise.

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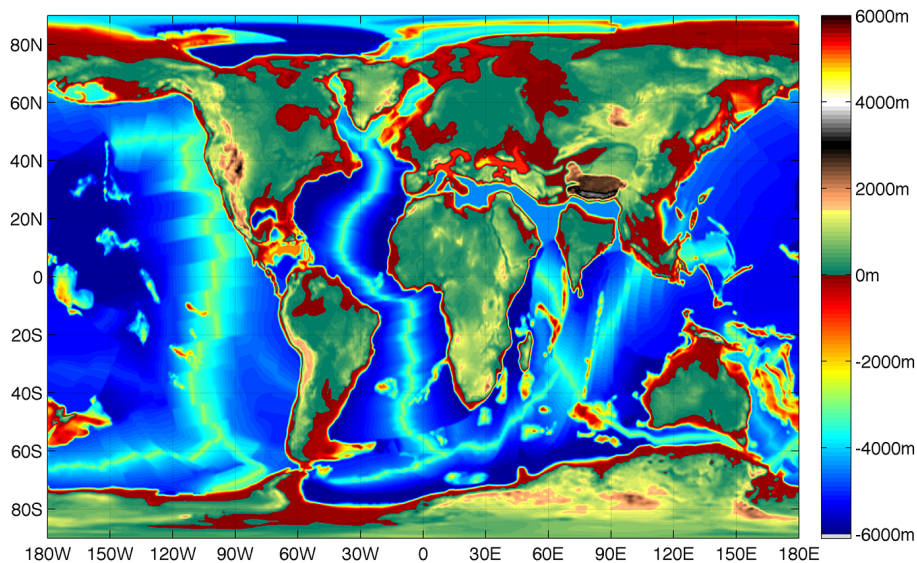


Figure 6. Final smoothed global topography and bathymetry reconstruction for the late Eocene at 38 Ma.

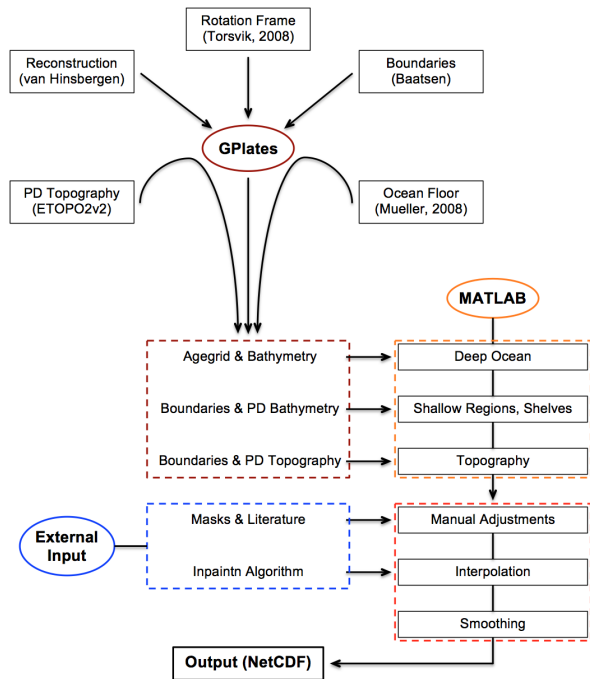


Figure 7. Flowchart of the procedure; the plate-tectonic reconstruction is made with GPlates, using a set of reconstructed plate trajectories (Seton et al., 2012; Hinsbergen et al., 2015), a reference rotational frame (Torsvik et al., 2008) and a set of boundary masks delimiting present day coastlines, continental shelf breaks, shallow ocean regions and some regions that need manual adjustments (see Figs. 1 and 4). In addition to the reconstruction, present day (PD) topography and bathymetry base files are manipulated using the same rotational frame and adjusted to the configuration at the aimed time frame. The resulting output files as well as some external input are then fed into a MATLAB script which builds up a global geography dataset through several consecutive steps and stores it as a NetCDF file.

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