EG UK Theory and Practice of Computer Graphics (2007)
Ik Soo Lim, David Duce (Editors)

A 3D visualisation environment modelling the evolution of north-west Europe since the Last Glacial Maximum

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Abstract

This work in progress aims to provide an interactive 3D visualisation allowing real time manipulation of glacial isostatic adjustment (GIA) model output data which reconstructs the ice distribution and coastline position in north-west Europe since the Last Glacial Maximum (LGM). The Lambeck GIA model is the current state of the art for European ice sheet and shoreline modelling and the work presented applies scientific visualisation techniques to an area of earth and ocean science that to date has not benefited from such technologies. The end application aims to eventually provide a real-time interactive 3D virtual world for scientists to explore the reconstruction data through direct manipulation. A recent study uses the Lambeck data as a basis for shelf sea palaeotidal reconstructions with profound implications for the environment, ecology and carbon cycle as the climate of north-west Europe has developed since the LGM. As the latter has only been seen in digital image form to date, the work of this project innovates by providing further user interaction, data interpretation and extraction from the GIA and palaeotidal models.

Categories and Subject Descriptors (according to ACM CCS):
J.2 [Computer Applications]: Earth and atmospheric sciences
I.3.8 [Computer Graphics]: Applications

1. Introduction

This work in progress will provide a real-time interactive 3D visualisation allowing the user to interact, via direct data manipulation, with a model showing the evolution of north-west Europe since the Last Glacial Maximum (LGM), 22,000 years ago. The graphics package will also incorporate a second model which reconstructs the shelf sea tidal environments over the same time scale and area with profound implications for understanding the environment, ecology and carbon cycle.

In 1995 and 1996 Lambeck [Lam95, Lam96] published detailed time-slice reconstruction data showing the evolution of north-west Europe since the LGM, based on glacial isostatic adjustment (GIA) modelling. These reconstructions show the distribution of ice and the position of the coastline as it evolved in response to both eustatic and isostatic change. To date the Lambeck output has been seen only as a series of digital images (Figure 1), or in static 3D block-model form, techniques which naturally limit the interaction between user and data.

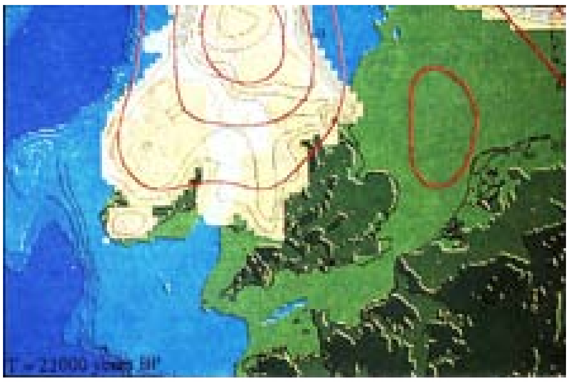

Figure 1: *Ice coverage and sea-levels in the UK during the LGM, as seen in the original Lambeck paper [Lam95]*

Many earth scientists currently underutilise the powers of exploration and analysis available by direct data manipulation using an interactive virtual environment [Bry96, PCL*03]. This project applies visualisation technologies to a novel data area and in doing so provides a modern scientific visualisation package, allowing earth and ocean scientists to manipulate and view the reconstruction data in new and previously concealed ways.

Throughout the geological past the Earth's climate has varied dramatically with serious consequences for the Earth's temperature, weather patterns and sea-level amongst other features. It is perhaps no coincidence that the recent explosion in the population of human beings has coincided with a notably stable period in the Earth's climate. As such our understanding of these systems will play a vital role in the ability of humans to withstand future changes.

By visualising state of the art climate reconstruction datasets this software will enable a better understanding of the earth's land, sea and ice interactions during past climatic events, and how these mechanisms affect local environments. This visualisation will be of benefit to anyone interested in the Earth's climate system and will provide a valuable tool for both research and educational purposes.

2. Glacial isostatic adjustment modelling

Sea-level changes are directly linked to the location, size and thickness of the ice sheets and the Earth's response to their load. Eustatic sea-level change occurs as terrestrial ice sheets grow or melt and water is stored or released respectively. Eustatic change is global in nature and its effects are immediate. Isostatic effects are the addition or removal of the substantial weight of an ice sheet over a landmass, which contributes to a sinking or rebounding of the Earth's crust respectively. These effects are global and occur over substantial time scales but their strongest impact is in the immediate vicinity of the ice sheets [Lam95].

Eustatic and isostatic effects combine to determine relative sea-level change (RSL) - the change in the elevation of the intersection of the sea surface with the solid Earth at any location - so that RSL can fall in response to eustatic fall or isostatic rebound, and vice versa.

As an indication of the scale of the changes modelled, during the LGM global eustatic sea-levels were on average 130m lower than the present day. However, under the weight of a 1500m thick ice sheet, central Scotland was 300m lower than its current position, therefore RSL at this location had risen despite a global fall in sea-level. Scotland is still rebounding from this load release today.

Geologists reconstruct past ice sheets and shorelines from geomorphological and sedimentary field evidence. The Lambeck model takes the observed geological data and combines this information with geophysical modelling which incorporates a numerical description of the rheology of the Earth's crust and upper mantle. It outputs a derived data set which has calculated grid values between the known data points. GIA models attempt to define the key parameters in the Earth system and the range of likely expected values for each parameter. Existing GIA models do not claim to be perfect representations of geological reality; rather they are progressively refined through the iterative nature of data-model comparison. As of the time of writing the Lambeck model is one of the best available for reconstructing European shoreline and coastal evolution [LP01].

3. Common Oceanographic visualisation techniques

Modern visualisation techniques used in areas such as medical imaging [WFM*05] and oil and gas exploration [YWT*05] have yet to be applied to these areas of ocean and earth science. Currently the simple and popular answer to viewing oceanographic data is to produce digital images in static or movie form. This method, despite its simplicity, is hindered by a lack of user interaction with the data.

While turnkey packages such as Matlab [1], PV-Wave [2] and Gnuplot [3] are very useful for charts, graphs and simple visualisations, they are limited by a primitive 3D interaction capability in real time and the 'black box' style of development which can be difficult or impossible to extend.

Application builders such as OpenDX [4] and Amira [5] provide the user with generic modules which can be combined via a visual programming paradigm, and as such benefit by allowing the relatively straightforward creation of complex visualisations. However the dataflow model is restrictive and whilst the modules are extensible this requires interaction with the applications builders' code and considerable programming skills.

3D engines (with open source examples such as Ogre [6] and Xith3D [7]) provide relatively straightforward ways to create interactive 3D virtual worlds. However, they too require programming skills to interface with the engine and may be restricted in functionality compared to a full graphics API.

A shift towards an up to date visualisation approach is an obvious need in the ocean sciences. New visualisation technologies provide potential solutions for an interactive 3D virtual world by running data sets in real time via a programmable graphics API. At the lowest realistic interaction level between the graphics pipeline and the coder are APIs such as OpenGL [8] and DirectX [9]. Whilst an API-based solution may be unsuitable for simple visualisations due to the programming overhead required in making any application; for complex models this technique is the most flexible, allowing the creation of a fully customisable interaction with the original data set.

Java3D [10] is a scene graph based graphics API running on top of OpenGL or Direct3D. Advantages include the use

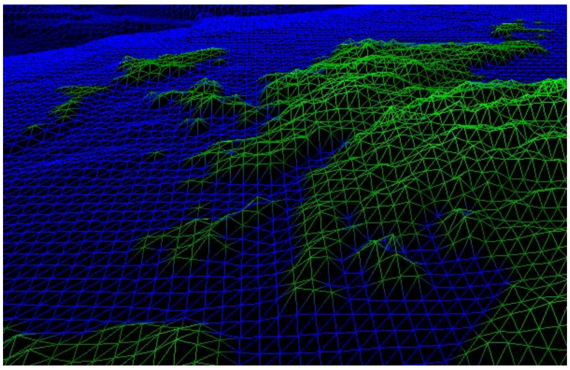

Figure 2: *North-west Scotland in the present day rendered in wire frame showing grid resolution between vertices*

of a standard Java package with its object oriented approach, portability between platforms and free access to development tools. For these reasons Java was chosen as the development platform and the decoupling from a very low-level API model led to the use of Java3D as the 3D scene graph environment. The authors have prior experience in creating landscape visualisations of this scale with Java3D and have found that it performs very well.

The oceanographic community commonly works with very large datasets. Examples of movie files showing relative sea-level change in Massachusetts Bay can be seen at [11], whilst common Matlab analysis tools can be found at [12]. A Java application providing a graphic exploration environment for viewing vertical ocean profile data is shown at [13]. Whatever tool is chosen to create a visualisation the nature of scientific data requires computer scientists and domain experts to combine forces. Only by bridging the gap of knowledge regarding what tools can be developed and how such ideas may be applied will produce ideal visualisations.

The scientists who will be using this visualisation need to visualise the raw data with a view to comparing and contrasting past climatic events. They also require the development of a flexible application that can easily be extended to other datasets. The nature of this visualisation means that a variety of users will benefit from the application and therefore a portable system that can be widely distributed and used by non specialists is also a pre-requisite.

4. The Lambeck data files

The Lambeck model outputs data from the south east tip of Iceland, east into Norway and south to the European Alps, corresponding to roughly 15W - 15E and 45N - 65N. Grid resolution of the model is 1/12 degree in both Latitude and Longitude, giving $241 * 361$ (87,001) nodes in the grid. In the north - south direction 1/12 degree longitude corresponds to 9.26km. Grid resolution in the east - west direction varies by a factor of cosine (latitude). At a latitude of 55N (the centre of the image) this corresponds to a resolution of 5.31km. Figure 2 shows a view of north-west Scotland in the present day, rendered in wire frame with each polygon vertex representing an entry in the data files.

The model is designed to show changes in RSL and ice coverage compared to the present day sea-level and altitude. To accomplish this, it uses a present day data file where altitude (in metres) is determined by a positive number and bathymetry by a negative. To reconstruct the past altitude the model outputs a series of 1000 year time slices dating back to 22,000 years before present (BP), with change in altitude from the present day value at each node recorded. A second set of files overlays this altitude series and shows whether ice coverage was present at each node, and if so, a thickness for the ice sheet at that location is given.

5. Rendering the Lambeck data

Visualising this data as a 3D environment required manipulation of the original files. A new set of files has been generated, one for each time slice by adding the present day altitude, the change in altitude and the ice thickness, thereby creating a file for each time slice in which the altitude (of land or ice) and bathymetry is recorded, with all values being relative to each years coastline. As in the original data set, the ice sheet files overlay this series informing whether each positive node is land or ice and the thickness of the ice.

The data files record the location of the node by the x and y position in the file, with each value recorded representing an altitude. Within the model this layout reads naturally into a global coordinate system, held as a series of 2D arrays with the location in the array representing position and value representing altitude. The application opens each of the files and sets its size and time series parameters from header information found at the beginning of each file before creating a series of objects, one for each time slice, holding altitude and ice (if present) arrays for each year. Dynamic loading in this manner creates a flexible application where data sets of any size and number of time slices can be loaded, providing the header format is followed and accepting the latitude correction which is currently set for north-west Europe.

The graphics software applies tried and tested visualisation techniques such as the data enhancement, mapping and rendering techniques in the Haber and McNabb reference model [HM90]. As discussed, this approach is novel for the earth and ocean sciences and allows for easy representation of information which was previously difficult to extract.

The software renders a polygon mesh in Java3D using the TriangleStripArray class (a subclass of the GeometryArray series) and by doing is able to load large arrays of data using minimum memory requirements. Each time slice renders one polygon mesh representing the surface of the Lambeck data at that point in time. Due to the original data format,

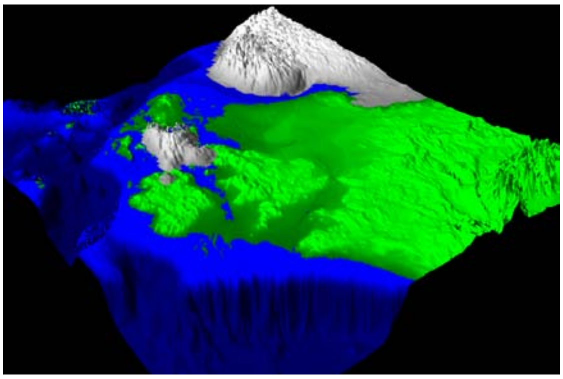

Figure 3: *North-west Europe as it was 16, 000 years ago, showing ice caps over Scotland and Norway and sea-level over 100m lower than the present day. Note that the sea floor is purposefully visible in this image*

determining land from sea is achieved by examining positive and negative altitude values. Determining land from ice is achieved by examining whether ice is present at each node in the ice array and rendering accordingly. Colour separation has been selected to visually enhance data interpretation and is represented to the user by colouring the land, sea or ice relative to altitude.

The loading of a new time slice is generated by an event from the GUI causing the selected year's array to be loaded into the strip array. Accessing this array in the 'by reference' mode enhances rendering performance and memory footprint. By loading each value into the model using relatively low level code rather than a visualisation tool, a great deal of functionality is easily added to the application that would be difficult to achieve otherwise. This is because the strip loading method within the rendering engine has total control over how and where each polygon's vertex will be plotted and as such modifying each value is a simple process.

6. The visualisation model

As the aim of this project is to create a 3D visualisation allowing direct user maniplation of the Lambeck model output, to date this project has successfully created an interactive environment in which to view this data. In doing so a Swing user interface is provided giving the user real time control over many of the properties of the image. Figure 3 shows a sample image viewing north-west Europe as it was 16,000 years BP. In this image the sea floor is visible, vertical relief is exaggerated and the colour scheme is chosen to highlight features of interest. Being able to set the properties of the image and the view position before starting and controlling an animation of the time slices is of great benefit to users and a great improvement on how this data could be viewed in the past.

A summary of some features provided by the user interface are:

- Automatic or manual time slice animation modes
- Variable colouring of land, sea and ice shading altitudes, allowing for height comparisons throughout the full model depth or on local scales (such as the Norwegian Trench) to be clearly seen
- Exaggeration of vertical relief to allow small variations in altitude to be examined
- Inclusion or removal of the sea surface allowing a realistic image or bathymetry to be examined
- Sea-level height can be set
- The image can be viewed as a grid square or corrected for latitude / longitude
- A movable camera position for observing local topography

With the above visualisation tools the system allows scientists to manipulate and view the Lambeck data in ways that have been impossible to date and by doing so gain new insight into previously imperceptible small scale changes. An example of the importance of these local changes would be the opening of the North Channel in the Irish Sea where scientists can examine changes in local topography as the channel opens up over time during the post glacial warming, shown in Figure 4. During the LGM the area that is now the Irish Sea was cut off from the Atlantic Ocean, with meltwater entering this area forming a swamp or lake. This is significant information for numerous environmental studies and visualisation of these changes provides a level of detail that was unavailable in previous images.

For the current data set the software outputs $87,001$ vertices and stores thirty six $(241 * 361)$ data arrays. It also contains a selection of arrays required by the strip array and runs with a maximum memory requirement of approximately

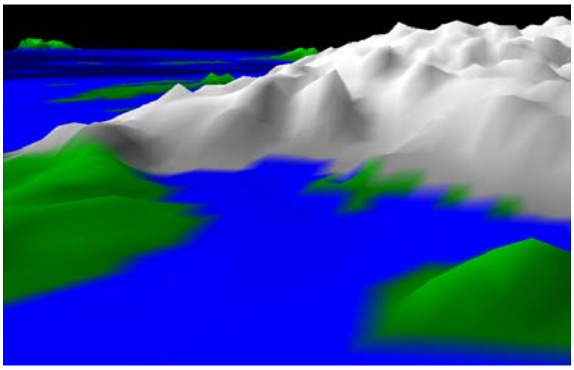

Figure 4: *View showing the North Channel in the Irish Sea 16,000 years BP with Ireland on the left, Scotland mostly ice covered and the Isle of Man bottom right. At this time the Atlantic Ocean was separated from the Irish Sea with large volumes of meltwater creating a swamp or lake in this region*

180Mb. The model could support approximately 2000∗2000 verticies which would allow entire continents to be rendered with an identical grid resolution, or a similar sized area to be rendered with a greater resolution. The application has yet to be tested on a selection of processors but runs in real time, well above fifty frames per second on a 2.8GHz Pentium IV processor with 1Gb RAM.

In animation mode the application must convert different datasets into 3D structures at each new time slice. This process could be achieved statically but would require a substantial memory capability. For this reason the decision was made to load each new image dynamically, thereby allowing the visualisation to run on a low specification PC. However, this slows the terrain generation down to around four new frames per second, provided normals are not generated for each new image.

The generation of normals roughly accounts for half the memory requirements and slows the maximum update speed to around one image per second on the development machine. Because of this constraint we have developed a faster animation algorithm using a set of pre-calculated normals to speed up the rendering process, which still gives good results whilst animating. Normal generation is of most use when the user has significantly changed the parameters of the image via interaction with the GUI and is given a choice of image quality via normal generation versus update speed through a menu in the GUI.

7. Future developments

As a work in progress this model has succeeded in its initial aim of creating an interactive virtual world of Lambeck's original data. As the application develops, three further areas have been identified for inclusion in this software:

7.1. Further interactive features

As the model has access to each data vertex at run time there is great potential to build on these features. The following requirements are currently being structured for development:

- Coloured contouring which shows comparative altitude locations
- Semi-transparent ghost images to allow a comparison to be made between time slices
- Picking techniques used to generate graphs showing RSL curves through time at user chosen locations, as shown for select locations in the original Lambeck paper [Lam95] and of great interest to earth and ocean scientists
- Picking also allows the user to view altitude data for selected locations and the placing of markers on the image surface, to measure height variation through time
- Measurement of distance between selected points and the output of digital images
- Volume rendering techniques applied to the time slice series, enabling the examination of interaction through time with the use of cutting planes

The above features are a result of consultation with the scientists who use the data. The software has been built on an extensible basic framework and inclusion of these and additional tools are dependent on the outcome of the shelf sea model detailed below, and the requirements of the ocean science advisors to the project.

7.2. Other Lambeck data areas

Lambeck has also produced identically formatted data for a variety of other locations throughout the world such as:

- Baltic Sea: a region affected by a large crustal deformation and prominent retardation of ice sheets
- Mediterranean Sea: morphological changes here are of interest to many geologists
- New Zealand waters: mathematically, a significant tidal change is expected to occur by a small bathymetric change
- Persian Gulf: a large shoreline change would be expected, which may have been of relevance to environmental changes in this area

As the software is designed using a modular approach, loading these areas and giving the user a choice of which data set to view simply requires the import of the measurements data. This will make it easy for the user to compare and contrast past climatic changes throughout the globe on identical time scales, which today is a time consuming task.

7.3. The European tidal model

An exciting further development which is still in its early stages uses the Lambeck output as a basis for reconstructing the hydrographic evolution of the European shelf seas [USH*06]. Such palaeotidal models (typically based on the Princeton Ocean Model [14]) use present day bathymetry determined from a number of sources such as the Proudman Oceanographic Laboratory, the British Geological Survey and the US National Data Centre. Palaeotidal models take the palaeoshoreline parameters as determined by Lambeck and use these to predict tidal amplitudes, tidal currents, mean high water spring tide, tidal mixing fronts and peak bed stress vectors [USH*06]. This tidal model runs with the same resolution and time steps as the original Lambeck model, with which it shall be integrated and is of great interest to scientists as it is the first shelf-wide palaeotidal model which can:

- Incorporate dynamic earth crust information from GIA output. This is important as vertical movements of the crust through time determine how coastlines and bathymetries evolve
- Reconstruct seasonal stratification dynamics, with profound implications for the role of shelf seas in the carbon cycle [RSUM07]

- Determine sediment dynamics. As such this model can be used as a predictive tool for determining offshore aggregate resources, and will help in predicting sedimentation and erosional responses to engineered changes in the shelf environment (such as wind farm construction). These predictions also form a basis for understanding the evolution of shallow marine habitats through time.

The successful visualisation of these data sets, combined with the Lambeck graphics package which is already successfully being used by the scientific community, will be used as a collaboration tool between research departments across universities and as a presentation aid at international conferences. For example, J. Scourse will use this software to present the tidal and CO_2 models at the 9th International Conference of Palaeoceanography, September 2007 [USH*06, RSUM07].

8. Conclusion

This work in progress has successfully created an interactive visualisation environment modelling the evolution of the Earth system since the Last Glacial Maximum. In doing so this application has provided a user interface allowing exploration and data manipulation of this virtual world, which is already of great use to scientists examining changes in palaeotopography. This is a first step in creating a 3D virtual environment detailing both the Lambeck and the palaeotidal model outputs.

The interactive nature of this application allows an examination of land, sea and ice evolution across time scales to be viewed on both local and model wide scales. This level of detail and control has not been seen to date and is expected to provide a mechanism for new hypotheses regarding the Earth's past climatic interactions, with implications for a wide range of earth science. GIA models explain a series of complex earth processes that occur on time scales difficult for humans to comprehend. A user-friendly visualisation of these systems assists cognitive understanding of these processes from school to postgraduate levels.

In the next stage of development further functionality will be added to the model. Once combined with the shelf sea data the application will have moved beyond sea-level / shoreline reconstruction and will be detailing oceanographic conditions such as past tidal interactions, with profound implications for our understanding of the evolution of the Earth system.

Over geological time scales the Earth's climate has varied dramatically. An ability to predict past climatic events has importance not only from a historical perspective but also for our ability to predict the future. For around the last 7000 years the climate of Europe and indeed the Earth has been notable by its stability, a time that has coincided with an explosion in the population of human beings. There seems no doubt that this increase in the human population on the Earth is now affecting the very climate we rely on, with anthropogenic warming due to greenhouse gas emissions a matter of serious current concern. As such our understanding of these systems will play a vital role in the ability of humans to withstand future changes. Despite strong evidence for abrupt and serious climatic changes occurring on timescales of centuries rather than millennia in the past, human beings seem to have difficulty in grasping the significance of these geological events. Any visualisation that can aid our understanding of the fact that despite all our technological achievements we remain an insignificant force compared to the Earth around us can only be of benefit.

9. Acknowledgements

The authors would like to thank contributions to this project from Prof. K. Lambeck, Dr. K. Uehara and A. Hopkins.

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Links

[1] Matlab: www.mathworks.com/ (13/03/07)

[2] PV-Wave: www.vni.com/products/wave/pvwave (14/03/07)

[3] Gnuplot: www.gnuplot.info (13/03/07)

[4] OpenDX: www.opendx.org (12/03/07)

[5] Amira: www.amiravis.com (13/03/07)

[6] Ogre: www.ogre3d.org (13/03/07)

[7] Xith3D: www.xith.org (13/03/07)

[8] OpenGL: www.opengl.org (13/03/07)

[9] DirectX: www.microsoft.com/windows/directx/default.mspx (13/03/07)

[10] Java3D: https://java3d.dev.java.net/ (13/03/07)

[11] Woods Hole circulation movies: http://woodshole.er.usgs.gov/operations/modeling/circulation.html (13/03/07)

[12] Woods Hole Matlab tools: http://woodshole.er.usgs.gov/operations/sea-mat/ (13/03/07)

[13] Java OceanAtlas: http://odf.ucsd.edu/joa/ (13/03/07)

[14] Princeton Ocean Model: www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/index.html (13/03/07)