A Three-Dimensional Animation of Climate Change Effects on Ocean Thermohaline Circulation

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ABSTRACT

The purpose of this project is to create a three-dimensional animation of the thermohaline circulation (THC), also known as the great ocean conveyor belt, based on output data from the National Center for Atmospheric Research (NCAR) Parallel Climate Model (PCM) for the years 2000 to 2099. The goal of creating the animations is to improve climate change understanding and science literacy among the general public through the use of three-dimensional visualizations. These animations would be the first to display ocean output data from the PCM in 3-D, hence, scientists may use the computer programs developed for this research to incorporate their own model-run scenarios into 3-D animations. Based on earlier analysis, a decrease in strength and a shift toward lower latitudes were predicted in the THC. Output from the PCM was in netCDF file format. Using the graphing capabilities of MATLAB, we visualized these assertions. Our results show that 3-D was not the best perspective to view changes in the THC. Reverting back to 2-D animations it was observed that, indeed, there is a southeastern and equatorward shift found. However, it was difficult to determine from the 2-D animations whether there was a change in the strength of the circulation.

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INTRODUCTION

The purpose of this project is to create a three-dimensional animation of the thermohaline circulation (THC), also known as the great ocean conveyor belt, based on output data from the Parallel Climate Model (PCM). The goal of the animation is to improve climate change understanding and science literacy among the general public. It is also hoped that scientists viewing the output data in three dimensions will gain new insights into the use of climate models.

Presently, most data analysis with the PCM has been done in 2-D. Our innovative approach is to animate into three-dimensions. Conveying the complex ocean circulation requires an upgrade from the 2-D visual analysis. Looking at the data in 3-D provides a new perspective of the ocean conveyor belt circulation because, in actuality, the ocean is seen in 3-D. Furthermore, a 3-D approach will yield a great benefit to the understanding of ocean climate dynamics. For example, we can easily analyze the shifts that are occurring in the ocean over time. It will also contribute to the advancement of 3-D animation techniques for viewing model output data.

The ocean is the largest reservoir of heat in the climate system (National Research Council Report (NRC), 2001). Present surface atmospheric forcings, i.e., the continued release of greenhouse gases from anthropogenic sources is leading to global warming. In fact, the ocean “has warmed by about .05°C averaged over the layer extending from the surface down to 10,000 feet, since the 1950’s” (National Research Council Report (NRC), 2001). Because the ocean can store great amounts of potential energy, the impact from present changes will not be completely realized. In any system, for example, the ocean, there will always be a striving to become equalized. During that process the climate continues to change due to external forcing, for example, radiative forcing, greenhouse gases, and aerosols. The ocean will actually never reach equilibrium. Therefore, the use of climate models is essential to assess the effects of present climate variability on the predicted climate response of the future.

We will focus on the characteristics of the ocean’s conveyor belt. These involve the density characteristics, which in turn are determined from the temperature, i.e., thermo, and salinity, i.e. haline, distribution. The freshwater supply in the ocean and global temperature are the main factors that determine the condition of the conveyor belt. Our goal is to illustrate the present conditions and the model’s prediction of the circulation 100 years into the future (2000-2099).

One can look at the THC beginning in the North Atlantic, where salty and warm surface waters cool as a result of making contact with the Arctic air mass. The increase in density due to the change in sea surface temperature (SST) creates downwelling of cold and salty water deep in the Atlantic, which then flows south along the east coast of North and South America, then east around Africa. When this flow reaches the Indian and Pacific Oceans, there is an upwelling of water because much of the cold water is heated at the surface in the Intertropical Convergence Zone (ITCZ). This return flow near the top of the ocean merges into surface currents and eventually joins the Gulf Stream and flows back into the North Atlantic to complete a global circulation.

Results from the PCM show a global warming trend through 2100 (Washington et al., 2000). The resulting increase in SSTs will significantly change the THC. Predictions include:

- The circulation in the North Atlantic will move into lower latitudes.
- The circulation will decrease in strength.
The Gulf Stream will change direction, away from its current flow towards Europe and moving more towards Iceland.

Freshwater precipitation will increase due to increased convection over the warming ocean, which will decrease the density of the ocean waters.

There are four factors controlling climate: location, elevation, latitude and ocean currents. The latter two are the major climate controls for Europe. Presently, the climate in Europe is warmer and wetter than it would otherwise be due to the influence of the THC. Though an increase in global temperature is projected, temperatures in Northern and Eastern Europe decrease considerably as seen over time in the PCM. This is because the weaker THC will lead to insufficient transport towards the pole of warm tropical water, which will eventually lead to cooler temperatures in the North Atlantic, decrease in precipitation locally, and perhaps a cooler Europe.

BACKGROUND
Model: Parallel Climate Model (PCM)

The Parallel Climate Model (PCM) is a coupled model consisting of the global atmosphere, ocean, land surface, and sea ice components. The state of the current climate is determined by the equations of fluid motion, radiative transfer, and parameterized small-scale processes. The model run begins in the 1870’s before the Industrial Era. This particular time period was chosen because anthropogenic emissions were considered to be too insignificant to alter climate conditions. The PCM was used in this research study for two reasons. First, the PCM has a substantially higher resolution than any other ocean and sea ice model, which makes the physical processes more realistic. Lastly, it is the model that Dr. Warren Washington, our science mentor, helped develop.

Various scientists have created and contributed different components for PCM use. The PCM makes use of the Department of Energy (DOE) Los Alamos National Laboratory Parallel Ocean Program (POP) for the ocean component of the model. For the ocean component, the average horizontal grid spacing is 2/3° with 32 levels, ranging from 12 meters from the ocean surface down to 5000 meters. A free surface is also included in which calculation of sea level changes are taken into consideration. Close to the equator, the grid spacing is approximately 1/2° in latitude, to capture the ocean dynamics in the equatorial region. The North Pole, as considered by the PCM, is placed over northern North America and eliminated to reduce the unnecessary computation. This was done because the grid points over the North Pole became too dense. This rotation was made so that the model may be able to capture the ocean dynamics near the North Atlantic, the region in the THC where we find the strongest current of dense water sinking. Due to this rotation, the ocean component is made more realistic and close to the observed (Washington et. al., 2001).

The ocean has a large heat capacity, which results in a longer temperature turnover rate. Changes that are presently occurring will take time to diffuse back into the atmosphere. Hence, this strengthens the importance of using climate models as predictive tools to determine the significant changes that are presently occurring.

Matrix Laboratory (MATLAB)

MATLAB was the chosen programming language to use for several reasons. First, it is interactive and user friendly. In many computer languages, such as FORTRAN and Java, the edit-compile-execute pattern is usually followed. If at any point variables are changed or an
error occurs, a recompilation is needed to view the new output. With MATLAB, however, no recompilation is ever needed when variables are modified. Once the program has compiled, the variables are retained in memory. If execution halts due to an error, successive commands can be typed into the MATLAB command prompt to continue executing. Second, MATLAB is compatible with output data from the PCM, which is in netCDF file format. Third, because MATLAB is also a graphical software, it has the capabilities of easily creating animation files (i.e. .avi and .mpg files) and still images (i.e. .jpg and .gif). The software provides powerful mapping toolbox that can present data in numerous map projections.

**METHODS AND DISCUSSION**

**MATLAB: 2-D Mapping Projections**

Figure 1 shows the native PCM grid, which is the grid used for computing. Modelers usually view their data in this form. It is showing the ocean current at 63 meters below the ocean surface. Relatively simple images, as in Figure 1, were created by simply plotting the matrix, which can be done by MATLAB as well as any other software. Area representation is skewed in the native grid. Asia is smaller than the real surface area. Antarctica seems bigger than actuality. Also, each i-index and j-index does not relate to any particular latitude or longitude. Only paired i and j indices correspond to a coordinate system. Hence, interpreting these types of map with indexes as references becomes cumbersome.

![Ocean Current at 63 meters](image)

**Figure 1:** Native grid of the PCM. Shows the ocean current at 63 meters below ocean surface.
To reduce these shortcomings, we make use of the MATLAB mapping projections. These map projections are powerful tools for providing users the flexibility of viewing their data in any type of perspective and shape, which eases data interpretation. Figures 2 through 5 show just some of the different projections available. Figure 3 displays the 3-D globe projection, which is useful if an added depth perception is needed for data investigation. Figure 4 is the Robinson projection, this type eliminates the initial distortion of the continents seen in Figure 1. Also notice that in each of the mapping projections displayed, the displaced pole over Canada is quite evident.

MATLAB: 3-D Animation

The region of study of the THC is the North Atlantic Basin, as seen in Figure 6. In this area, the strongest downwelling of ocean current in the circulation is found. Figures 7 through 9 are three still images of the three-dimensional animation created in this project. The original animation shows the progression of the ocean current every five years from 2000 through 2099 with an isosurface of 5 cm/s. An isosurface is an area of constant value. Hence, MATLAB contours and overlays the red surface area in regions where the current is equal to 5 cm/s. A depth range from 63 meters to 500 meters from the ocean surface was chosen to best view the Gulf Stream and also to avoid the effects of surface winds.

The Gulf Stream’s characteristics tube-like shape is clearly visible as it moves into higher latitudes in all three images. It actually outlines the East Coast of North America. As it travels up to the Arctic, the tube-like current dissipates. In that area, it is projected that the greatest amount of dense ocean water sinks to ocean depth (i.e., the bottom). Two main projections from the PCM output prompted questions for this project. Would changes in strength of the THC be apparent, and is it clearly seen that the circulation is moving into lower latitudes in 3-D? Based on the visualizations, 3-D was not the appropriate perspective to view changes in the THC. Therefore, we reverted back into 2-D visualizations.

MATLAB: 2-D Animation

Ocean Current

Figures 10 through 12 are still shots of 2-D animation of the Gulf Stream. The animation iterated every year from 2000-2099. Because the ocean current is a scalar value, only magnitude can be determine from the animations and the direction of flow has not been taken into account. As can be seen in Figure 10, the strongest current is found in the East Coast of North America. Ocean current reaches up to 60 cm/s moving into the higher latitudes. In the year 2050, Figure 11, the strong current from the Gulf Stream, indicated by much of the red shading, is still apparent. By the end of the model run, Figure 12, there is less red areas found which indicate a weakening of the THC. However, it was still difficult to determine whether there were changes occurring in the THC. To further investigate, we extended our analysis by looking at the ocean current anomalies.

Ocean Current Anomaly

Figures 13 and 14 are speed of ocean current anomalies in the Gulf Stream. An anomaly is defined as a deviation from the mean. The mean value was taken by averaging the ocean current from the first decade, years 2000 through 2099. The years following 2010 were subtracted from the mean to calculate the deviation from the normalized value. In the year 2000, Figure 13, there was not much change from the average mean as indicated by the green, yellow, and light-blue color shadings. A near zero anomaly was expected for this run because year 2000
was contained in the calculation of the mean. By the end of the century, Figure 14, the model run scenario shows in parts of the North Atlantic current both positive and negative anomalies which implies shifting into lower latitudes. Notice that more positive anomalies are found at lower latitudes and the largest change of ocean current found over England.

CONCLUSIONS AND FUTURE WORK

Three Dimensions vs. Two Dimensions

The goal of this research project was to animate output data from the PCM. This was successfully accomplished. As a result of conducting this project, it was realized that the merits of 3-D versus 2-D animations were relative. Data analysis is dependent on how it is interpreted. For example, 3-D adds depth. This was very useful when the THC was analyzed. Visualizing the depth of the ocean was necessary to fully capture the strong ocean currents. On the other hand, creating 3-D visualizations is relatively more complicated than 2-D. Because of that complexity, for this study, creating isosurfaces to represent data values was the only method used in 3-D.

The use of 2-D also provides great contributions. It can display more than one value for each variable, hence the use of the colorbar. Nevertheless, 2-D does not have the capability of analyzing the many layers of the ocean depth. Only one layer was analyzed at a time.

For our case, 2-D animation was the best perspective to view the variations in the THC as it progressed through time. The ocean current anomaly was a major indicator in determining the shift of the THC, although the strength is still not clearly observed. A 3-D conversion was suggested after the completion of the 2-D animations. This was not developed further because we did not believe the added perspective would provide us with any new and relevant information.

Based on preliminary data analysis, it’s possible that the Gulf Stream will shift to the south, but maintain the same intensity. Such a shift may entail northern Europe becoming cooler than it would otherwise be or possibly warming less than the average global warming. Further analysis is needed to elaborate on the specific details of such impacts. Also, because the THC is a global ocean circulation, many parts of the world may dramatically change due to slight changes in the flow of the THC. Hence, it could be possible that other changes may occur but, for this limited region of study, they have not been fully analyzed and addressed.

Many programming codes were developed in MATLAB in the process of creating animations. Mark Petersen will be continuing this research in hopes that all tools and techniques learned and used will be made accessible to other scientists who wish to replicate the methods from the present study in future animations.

REFERENCES


Figures 2 – 5: Ocean current at 63 meters below the sea surface

Figure 2

Cassini Cylindrical Projection

Figure 3

Globe Projection

Figure 4

Robinson Projection

Figure 5

Equal-Area Cylindrical Projection

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Figure 6: North Atlantic Basin. This is the area of the thermohaline circulation (THC) where strongest downwelling of water is found.

Figure 7: 3-D ocean current in the North Atlantic Basin, year 2000, with an isosurface of 5cm/s
Figure 8: 3-D ocean current in the North Atlantic Basin, year 2050, with an isosurface of 5cm/s

Figure 9: 3-D ocean current in the North Atlantic Basin, year 2099, with an isosurface of 5cm/s
Figure 10: Ocean current over the North Atlantic basin, year 2000

Figure 11: Ocean current over the North Atlantic basin, year 2050
Figure 12: Ocean current over the North Atlantic basin in the year 2099.

Figure 13: Ocean current anomaly over the North Atlantic basin, year 2000.
Figure 14: Ocean current anomaly over the North Atlantic basin, year 2099.

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