Using Generative Art to Convey Past and Future Climate Transitions

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Abstract

The ability to understand modern day climate relies on a foundational understanding of past climate variability and the ways in which the planet is stabilized by interconnected feedbacks. This article presents a unique method for translating records of past climate transitions preserved in deep-sea sediments to broad audiences through an immersive visualization. This visualization is a multimedia installation that incorporates geochemical records of glacial and interglacial transitions and model predictions for future anthropogenic warming to create an immersive experience for viewers, inviting them to engage with and reflect on the subtle, nuanced differences between subsets of Earth's history. This work showcases five intervals of time, beginning with the inception of modern glacial-interglacial cyclicity (~one million years ago), comparing past climate with model results for projected future anthropogenic warming (until 2099). The installation consists of several experimental projections, one for each subset of time, displayed on different surfaces in a room. As viewers move through the space, the projections slowly cycle through different climatic transitions, using animation methods like speed, color, layering, and repetition, all generated through site-specific data to convey the planet's unique behavior as it relates to global climate. This work provides a framework for unique scientific data visualization, with generative animations created using a Perlin Noise algorithm at the center of the installation. Research variables, like sea surface temperature, nutrient dynamics, and the rate of climate change, impact formal outcomes like color, scale, and animation speed, which are all easy to manipulate and connect to specific data. This approach also allows the possibility of publishing data online and provides a mechanism for scaling visual parameters to a wide variety of quantitative and qualitative data.

Introduction

Generative art and the methods employed here allow for the direct translation of quantitative data into animations while preserving the integrity of the data. Artists use generative art to explore perceptions of space and time[1,2], but generative art is not yet commonly used with spatial or temporal scientific data. The work presented here provides a simple framework for using generative visual products to showcase climate data. These products can be widely applied, whether used to create in-person exhibits or as a visual aid for a presentation or online publication.

Using geochemical measurements or estimates to scale elements such as color, shape, size, and speed provides a means of visually conveying rates and magnitudes of change without requiring the viewer to read a paper, interpret a graph, or look through a data table. Alternatively, the randomization of selected variables is used to convey a lack of data or uncertainty, as in the case of future projections. The juxtaposition of geologic past and future is perhaps integral to the effectiveness of these products as science communication tools. Recent experiences often serve as the baseline of comparison for modern climate change, making it difficult to grasp the magnitude of anthropogenic climate change[3].

Geochemical measurements visualized in this paper span the mid-Pleistocene transition (MPT; 1.2 million to 600,000 years ago), recording changes near the northern boundary of the Southern Ocean from International Ocean Discovery Program Site U1475[4,5]. The MPT data is presented in four animations, which highlight changes in ocean conditions as the planet cools and glacial and interglacial variability is amplified[6]. This provides a geologic baseline revealing the natural rhythm of Earth's climate, emphasizing a long-term cooling trend that starkly contrasts future climate projections. Future temperature estimates are average values of the results of 20 climate models under the forcings of Representative Carbon Pathway 8.5 (RCP 8.5; scenario with a radiative forcing of 8.5 W/m^2 in the year 2100) for the location New York, NY[7]. RCP 8.5 represents a worst-case scenario of sustained emissions resulting in a 3.7 °C increase in average global temperature by 2100[8]. Thus, this article demonstrates a means of comparing future projections with geologic data to compare rates of climate change and climate variability.

Protocol

1. Playing the existing visualizations

1. Download coding and visualization software (see **Table of Materials**).
    1. Download the data and code. This article uses 'degrees of uncertainty' with data from Marcks et al.[4] and Cartagena-Sierra et al.[5] on the age model from Starr et al.[9].
    NOTE: The 'degrees of uncertainty' contains five coding files, **Supplementary Coding File 1, Supplementary Coding File 2, Supplementary Coding File 3, Supplementary Coding File 4**, and **Supplementary Coding File 5**, with contents pertaining to each time period of visualization (MPT 1, MPT 2, MPT 3, MPT 4, and Future, respectively). Each of these contains coding libraries[10] used for visualizations as well as 'Script' folders containing

downloaded data in .csv format, code used to generate visuals 'particle.js', and an index file 'index.html' which links all relevant data and code together.

2. Open the code editing software from the 'degrees of uncertainty'.
3. Drag a file (MPT 1, MPT 2, MPT 3, or MPT 4) into the code editor to visualize it.
    1. The files appear in the EXPLORER menu on the left-hand side of the window. Check the procedure for visualizing data from the 'Future' folder in step 1.7.
4. In the EXPLORER menu, click on the folder (**MPT 1, MPT 2, MPT 3**, or **MPT 4**) to reveal a drop-down menu, click on **script**, and then click on **index.html**.
   NOTE: The code appears on the right-hand side of the window.
5. Left-click the portion of the window with code for 'index.html' and select **open with live server** from the menu.
   NOTE: An internet browser window opens and begins playing the visualization.
6. Closing and reopening the code editor may be necessary between visualizations when loading a visual from a different subset of time. Repeat steps 1.4-1.6 for each subset of time.
7. To view the visualization based on future projections, open the 'Future' folder on the computer and drag either the 'Accumulation' or 'Transition' folder into the code editor. The difference between animations is described in the results section.
8. Select the folder name in the EXPLORER window and click on **index.html**. Left-click the portion of the window with code for 'index.html' and select **open with live server** from the menu.
   NOTE: An internet browser window opens and begins playing the visualization, which can be saved locally on a computer by screen recording.

2. Editing the visualizations

NOTE: To edit the visualizations, follow steps 1.1-1.4 above, as necessary, to load the relevant data.

1. Select the folder of interest in the EXPLORER window of the code editor and open the main script file by clicking on **sketch.js**.
   NOTE: The 'sketch.js' file in the MPT 1 (**Supplementary Coding File 1**) contains the most detailed annotations; thus, this file may be the most useful for familiarizing the code.
    1. The code appears on the right-hand side of the code editor window. Perform any edits to visualization parameters within this code. Look for code annotations with detailed descriptions of the code and its function following double slashes "//" and further identified by green text (**Supplementary Figure 1**).
    2. Define the variables that will be linked to data or used to customize visual parameters (**Supplementary Figure 1**).
    3. Load the data into the workspace (**Supplementary Figure 2**).
    4. Define the visual parameters of the canvas. Use a 'for' loop to link data to specific characteristics; here, size is linked to nitrogen isotopic value 'd15N' (**Supplementary Figure 3**).

5. Use a for loop to define a tail length for each orb. The tail refers to the length of time that the orbs remain on screen after appearing, creating an accumulation of color as the visual progresses (**Supplementary Figure 4**).

   NOTE: Here, the tail length is scaled to the accumulation rate of alkenones' c37.

6. Finally, draw the animation, applying a Perlin Noise algorithm[11] to define the shape of the visuals (**Supplementary Figure 5**).

   NOTE: Here, a circle is used as the base shape with noise applied to the points along the circumference of the circle. These will 'wiggle' the boundary of the circle, yielding an organic orb-like shape that deviates from a circle in an amount defined by the 'wiggle' command.

7. Edit the code as necessary using annotations to aid the alterations.

3. Saving the edits

1. Save the edits by pressing the **command** and **S** keys at the same time.

2. View updated visuals by navigating to the 'index.html' file in the EXPLORER window, left-clicking, and selecting **open with live server** from the menu.

   NOTE: An internet browser window opens and begins playing the visualization, which can be saved locally on the computer by screen recording.

Representative Results

This work produces six visualizations corresponding to five unique intervals of geologic time, with visual aspects scaled to quantitative data either measured on deep-sea sediment (**Figure 1**, **Figure 2**, **Figure 3**, **Figure 4**, **Video 1**, **Video 2**, **Video 3**, and **Video 4**) or modeled from the Intergovernmental Panel on Climate Change's (IPCC) RCP scenarios (**Figure 5** and **Figure 6**). Each visualization is unique and generative, meaning the same input data yields slightly different visual outputs each time the code is run due to the randomization of variables such as particle trajectory and shape boundaries. In each visualization, orbs-created from a Perlin Noise algorithm applied to the points around a circle-traverse across a black background with semi-transparent tails recording their trajectories. The orbs continue moving across the screen indefinitely, ultimately accumulating color atop the black background.

In **Figure 1**, **Figure 2**, **Figure 3**, and **Figure 4**, generated from code in MPT 1-4 (**Supplementary Coding File 1, Supplementary Coding File 2, Supplementary Coding File 3**, and **Supplementary Coding File 4**), elements such as color, size, and speed are quantitatively scaled to estimates of sea surface temperature, nitrogen isotopic composition, and the rate of climate change based on geochemical measurements of deep-sea sediment. The color ranges from blue to red, with the coldest intervals marked by the greatest abundance of blue orbs and the warmest intervals dominated by red orbs[5]. This is accomplished by changing the numeric value of Red in the Red, Green, Blue (RGB) color values, while Green and Blue values are held constant. The Red value varies between 0-200 depending on sea surface temperature estimates, with higher temperatures corresponding to a greater Red value. The size of each orb is scaled to the nitrogen isotopic composition of planktonic foraminifera, which is related to the amount of nutrients and carbon consumed by phytoplankton[4]. The size of each orb varies between 1-10, with larger sizes corresponding to higher nitrogen isotopic values. The speed of each orb as it moves across the screen is scaled to the rate of climate change, estimated as the number of glacial and interglacial periods within an interval of time divided by the number of years each interval spans, with glacial and interglacial boundaries as defined in Lisiecki & Raymo[11].

Figure 5 and **Figure 6** (**Video 5** and **Video 6**) arise from projections of annual average temperatures for New York, NY[7]. The location of New York was selected as it is the closest city with data available to the location of the projection installation. Both **Figure 5** (**Video 5**) and **Figure 6** (**Video 6**) scale color to temperature estimates, with cooler temperatures marked by greater Green values in the RGB decimal code, while Red and Blue color values remain constant, resulting in a more orange coloration. Future animations rely on random number generation to determine the size and speed of each orb, as these parameters are required to create these visualizations, but the corresponding numeric values remain uncertain in future projections. **Figure 5** (**Video 5**), generated with the 'Accumulation' code, is a similar animation to the MPT visuals; orbs have semi-transparent tails, and the continued movement of orbs across the canvas results in an accumulation of color. **Figure 6** (**Video 6**), created with the 'Transition' code, is a more simple visual with no tails, instead showing only the outline of orbs moving across a black background.

The product format allows for the customization and presentation of data in a number of ways. Screen recordings of the animations generated with this code are used to create immersive science communication exhibits by simply connecting a computer or laptop to a projector and setting up a suitable display space. Immersive and interactive exhibits are created by staging a gallery with several projectors, easels, foam boards, a side table with a microscope, deep-sea mud, and microfossils for guests to examine (**Figure 7** and **Figure 8**). This gallery allows for a directional flow of foot traffic, where visitors enter a room with four foam boards supported by easels. Each board serves as a canvas for projecting one of the MPT[4,5] visuals (**Figure 7**). As the viewer walks into the room, beyond the MPT projections, another projector displays the Future visuals across the walls and floor of the gallery, inviting the viewer to "walk into the future" (**Figure 8**). Beyond the Future projection, a table is set up with a dissecting microscope, microscope slides containing fossil plankton and deep-sea sediment, and information explaining how scientists use deep-sea mud to understand past climate and refine future climate projections. Ultimately, this work transforms oceanographic and climate data spreadsheets into graphics that serve as the basis of an immersive installation, inviting the audience to walk through geologic time and witness our climate change due to natural and anthropogenic drivers.

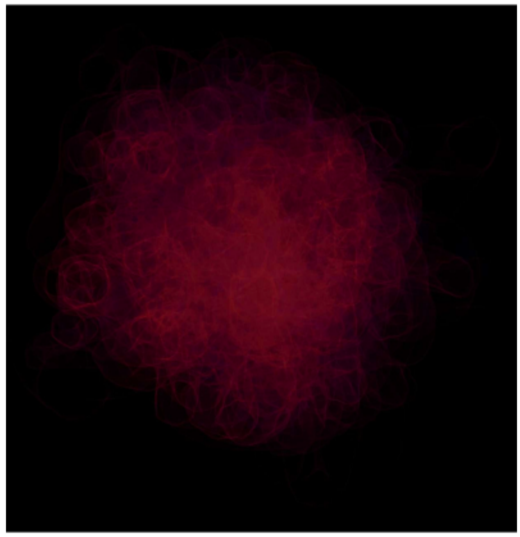

Figure 1: Image generated from MPT 1 data and code. This shows the earliest time segment (~1.2-1.118 million years ago) prior to glacial-interglacial lengthening and glacial cooling. Orbs represent unique data values, where RGB color values are scaled to alkenone-based sea surface temperature estimates[5], and size increases as a function of the nitrogen isotopic composition of foraminifera[4], which is related to the ability of primary producers in the ocean to take up carbon at IODP Site U1475. This is a still image taken from **Video 1**. Please click here to view a larger version of this figure.

Figure 2: Image generated from MPT 2 data and code. This shows the second earliest segment of time (~1.112-1.06 million years ago), which is immediately prior to glacial-interglacial lengthening and glacial cooling. Orbs represent unique data values, where RGB color values are scaled to alkenone-based sea surface temperature estimates[5], and size increases as a function of the nitrogen isotopic composition of foraminifera[4], which is related to the ability of primary producers in the ocean to take up carbon at IODP Site U1475. This is a still image taken from **Video 2**. Please click here to view a larger version of this figure.

Figure 3: Image generated from MPT 3 data and code. This shows the second latest segment of time, when glacial-interglacial cycles lengthen (~1.06 million to 900,000 years ago). Orbs represent unique data values, where RGB color values are scaled to alkenone-based sea surface temperature estimates[5], and size increases as a function of the nitrogen isotopic composition of foraminifera[4], which is related to the ability of primary producers in the ocean to take up carbon at IODP Site U1475. This is a still image taken from **Video 3**. Please click here to view a larger version of this figure.

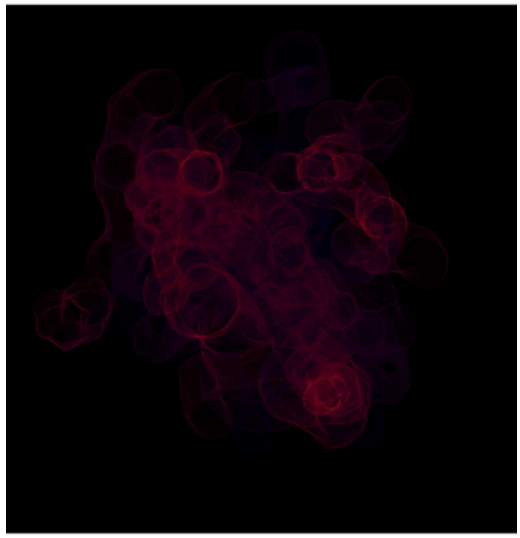

Figure 4: Image generated from MPT 4 data and code. This shows the most recent segment of time, when longer glacial-interglacial cycles were more established (~900,000-600,000 years ago). Orbs represent unique data values, where RGB color values are scaled to alkenone-based sea surface temperature estimates[5], and size increases as a function of the nitrogen isotopic composition of foraminifera[4], which is related to the ability of primary producers in the ocean to take up carbon at IODP Site U1475. This is a still image taken from **Video 4**. Please click here to view a larger version of this figure.

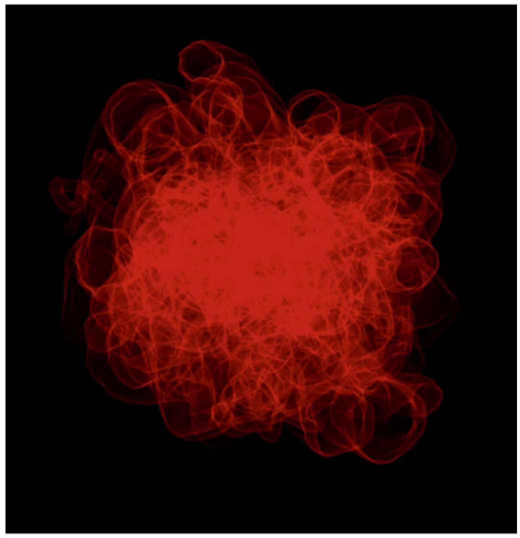

Figure 5: Accumulation image generated from Future data and code. This shows a model projection for future anthropogenic warming based off of temperature estimates of RCP 8.5 model averages for New York, NY[7]. The size and speed are randomized as the ability of primary producers in the ocean to take up carbon, and the rate of climate change is uncertain. This is a still image taken from **Video 5**. Please click here to view a larger version of this figure.

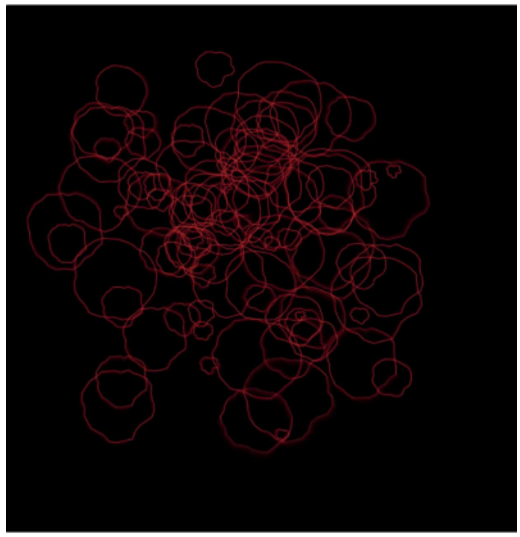

Figure 6: Transition image generated from Future data and code. This shows a model projection for future anthropogenic warming based off of temperature estimates of RCP 8.5 model averages for New York, NY[7]. The size and speed are randomized as the ability of primary producers in the ocean to take up carbon, and the rate of climate change is uncertain. This is a still image taken from **Video 6**. Please click here to view a larger version of this figure.

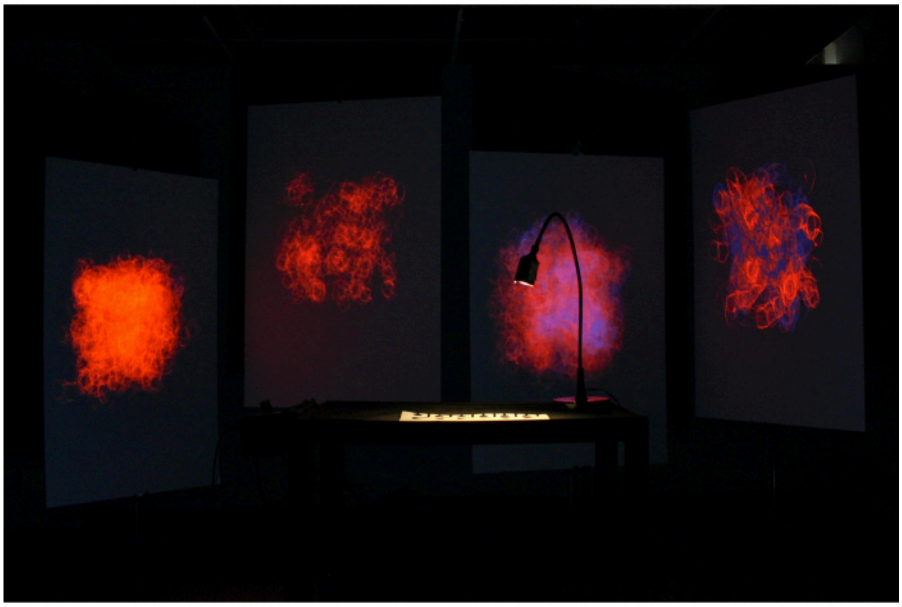

Figure 7: Image of the four-panel projection installation where MPT data is displayed behind a viewer and lighted information table. This shows a portion of the installation, as the viewer enters the room where the earliest MPT data is presented. **Video1**, **Video 2**, **Video 3**, and **Video4** are individually projected on each panel, in order from left to right. Please click here to view a larger version of this figure.

Figure 8: Image of the immersive wall projection. This shows the viewers walking past an animation of Future temperature estimates from RCP 8.5 model averages for New York, NY[7]. In this animation (**Video 5**), the RGB Green color value was increased significantly, yielding a more yellow-colored visual. Please click here to view a larger version of this figure.

Video 1: Animation generated from MPT 1 data and code. This shows a screen recorded video of the animation generated from MPT 1 data and code. This corresponds to the earliest time segment (~1.2-1.118 million years ago) prior to glacial-interglacial lengthening and glacial cooling. Orbs represent unique data values where, RGB color values are scaled to alkenone-based sea surface temperature estimates[5], and size increases as a function of the nitrogen isotopic composition of foraminifera[4], which is related to the ability of primary producers in the ocean to take up carbon at IODP Site U1475. Please click here to download this Video.

Video 2: Animation generated from MPT 2 data and code. This shows a screen recorded video of the animation generated from MPT 2 data and code. This corresponds to the second earliest segment of time (~1.112-1.06 million years ago), which is immediately prior to glacial-interglacial lengthening and glacial cooling. Orbs represent unique data values, where RGB color values are scaled to alkenone-based sea surface temperature estimates[5], and size increases as a function of the nitrogen isotopic composition of foraminifera[4], which is related to the ability of primary producers in the ocean to take up carbon at IODP Site U1475. Please click here to download this Video.

Video 3: Animation generated from MPT 3 data and code. This shows a screen recorded video of the animation generated from MPT 3 data and code. This corresponds to the second latest segment of time, when glacial-interglacial cycles lengthen (~1.06 million to 900,000 years ago). Orbs represent unique data values, where RGB color values are scaled to alkenone-based sea surface temperature estimates[5], and size increases as a function of the nitrogen isotopic composition of foraminifera[4], which is related to the ability of primary producers in the ocean to take up carbon at IODP Site U1475. Please click here to download this Video.

Video 4: Animation generated from MPT 4 data and code. This shows a screen recorded video of the animation generated from MPT 4 data and code. This corresponds to the most recent segment of time, when longer glacial-interglacial cycles were more established (~900,000-600,000 years ago). Orbs represent unique data values, where RGB color values are scaled to alkenone-based sea surface temperature estimates[5], and size increases as a function of the nitrogen isotopic composition of foraminifera[4], which is related to the ability of primary producers in the ocean to take up carbon at IODP Site U1475. Please click here to download this Video.

Video 5: Accumulation animation generated from Future data and code. This shows a screen recorded video of the animation generated from Future data and code. The color is scaled to a model projection for future anthropogenic warming based off of temperature estimates of RCP 8.5 model averages for New York, NY[7]. Size and speed are randomized as the ability of primary producers in the ocean to take up carbon, and the rate of climate change is uncertain. A tail is permitted in the code, resulting in an accumulation of color. Please click here to download this Video.

Video 6: Transition animation generated from Future data and code. This shows a screen recorded video of the animation generated from Future data and code. The color is scaled to a model projection for future anthropogenic warming based off of temperature estimates of RCP 8.5 model averages for New York, NY[7]. Size and speed are randomized as the ability of primary producers in the ocean to take up carbon, and the rate of climate change is uncertain. No tail is permitted in the code, resulting in no accumulation of color. Please click here to download this Video.

Supplementary Figure 1: Image of coding software and code defining variables that will be linked to data or used to customize visual parameters. Please click here to download this File.

Supplementary Figure 2: Image of coding software and code which loads data into the workspace. Please click here to download this File.

Supplementary Figure 3: Image of coding software and code which defines visual parameters of the canvas and applies a for loop to link data to specific visual characteristics. Please click here to download this File.

Supplementary Figure 4: Image of coding software and code which applies a for loop to define a tail length for each orb. Please click here to download this File.

Supplementary Figure 5: Image of coding software and code which draws the animation, applying a Perlin noise algorithm to define the shape and movement of visuals. Please click here to download this File.

Supplementary Coding File 1: The 'degrees of uncertainty'_MPT 1. Please click here to download this File.

Supplementary Coding File 2: The 'degrees of uncertainty'_MPT 2. Please click here to download this File.

Supplementary Coding File 3: The 'degrees of uncertainty'_MPT 3. Please click here to download this File.

Supplementary Coding File 4: The 'degrees of uncertainty'_MPT 4. Please click here to download this File.

Supplementary Coding File 5: The 'degrees of uncertainty'_Future. Please click here to download this File.

Discussion

This work highlights the utility of generative art for the purpose of science communication. The workflow can be used to translate existing data to elements within an animation. While the animation outputs from this work are unique in that each time the code is run a different version of the animation is created, the visual elements are scaled to geochemical and climate model data; thus, elements such as color, speed, and size remain constant, so long as the input data remains the same. This also allows for the direct comparison of these visual elements to draw conclusions about the data.

Geochemical measurements from deep ocean sediments and model estimates for future anthropogenic warming are used within a Perlin Noise algorithm[11] and transformed into immersive installations. Animations generated from paleoceanographic data serve as a baseline of comparison for the model estimates of future temperatures. Deep ocean sediments are an archive of past climate and an invaluable resource for understanding the climate system[12,13]. Visuals are generated with a Perlin Noise algorithm, selected for its ability to smoothly move the boundary of generated shapes. Here, a Perlin Noise algorithm is applied to the points outlining a circle, ultimately creating an organic shape which smoothly moves across the background. The circle is selected due to its similarity in shape to the cross section of a sediment core, as well as the similarity to a cell once noise is added to the outline. This generates organic shapes which touch on the nature of these geochemical records as they come from marine primary producers, or small organisms which photosynthesize and consume nutrients and carbon in the ocean[13]. These organisms both change global climate through the consumption of carbon and record past changes in the ocean through the preservation of climatic signals in the chemical makeup of their shells, which are preserved in ocean sediments. The layering of shapes, or orbs, in each visual creates an accumulation of color within the animations and hints at the preservation of these paleoceanographic records, which are preserved through the layering of sediment within ocean basins, further tying visuals to geologic processes.

The Red, Green, Blue (RGB) decimal code is used to quantitatively scale color with temperature estimates from marine primary producers which are measured on alkenones, or long carbon chains whose structure varies with temperature[5]. In these visuals, red and orange colors indicate warmer temperatures. Different colors are used in the scaling of geochemical data and future projections as the data used here are not directly relatable (due to the nature of available projection data and the regions of interest to the authors). In future iterations, the color can be scaled similarly between all animations to allow for the direct comparison of data.

The speed of orbs is defined by the relative rate of climate change, estimated as the number of glacial or interglacial stages divided by time in years. This is calculated by counting the number of glacial or interglacial periods in each interval of time, with each period defined by Lisiecki & Raymo[12]. The Future projections (**Figure 5** and **Figure 6**) have randomized speeds as they do not cover a complete glacial or interglacial cycle and reflect a significant deviation from the natural rhythm of Earth's climate. Meanwhile, the randomization of data is not clear in the visuals and serves perhaps more as a necessary step in ensuring that a visual can be made even in the absence of data, rather than being a significant symbol of uncertainty to the viewer. There is certainly room to experiment in future iterations on how to convey uncertainty in more poignant forms, as uncertainty is not trivial in the ability to understand future climate.

The size of orbs depends on the nitrogen isotopic composition of fossil plankton, a proxy for the uptake of nutrients and carbon by primary producers, which may exacerbate or mitigate climate change; it was chosen as it represents a link between biology and global climate[13]. It remains uncertain to what extent biology may be able to compensate for future rises in atmospheric carbon dioxide, but the incorporation of this data into visuals serves as a reminder to the complexity of the climate system and the intersection of biology and geology. Similarly to the speed of orbs, in Future projections, no data exists for this metric, thus randomized speeds are used in the absence of data. Other iterations of this work may replace the nitrogen isotopic composition of foraminifera with the oxygen isotopic composition of benthic foraminifera, which is assumed to reflect global changes in temperature and ice volume[12]. Despite challenges in juxtaposing animations of past and future, this work highlights the differences between natural and anthropogenic climate change and serves as a useful first step in the creation of generative climate art.

In order to integrate animations into tangible experiences, projection techniques are used to create an immersive exhibit in which guests walk through geologic time and into the future. It is important to note that temperature projections from RCP scenarios are not directly relatable to past sea surface temperatures, and proxies from the geologic record are imperfect and hold their own biases. Nonetheless, this work provides a foundation for the inclusion of deep-sea geochemical records and climate model outputs into modern art, while also eliminating barriers of entry to climate science.

This work relies on the audience's abstract intuition to discern differences between these discrete subsets of time, providing a novel means of engagement with scientific data. Without relying on text, audio, or the background knowledge needed to accurately interpret data, viewers gain a sense for the magnitude and rate of climate change through discrete subsets of time with simple elements such as color and speed guiding their intuition. This work is not without limitations; as noted above, clear discrepancies exist in data availability, comparability, and location. While we have limited these animations to the author's regions and time periods of interest, this protocol can be easily applied to data from many more locations, spanning different intervals of time, and shared in formats we have not yet explored. Further, during the exhibitions of these animations, viewers were aided by posters, microscope displays, and brief verbal explanations which provided context essential to understanding the purpose of the exhibit. While this study did not assess the effectiveness of this strategy on science communication, future work would benefit from surveys or a social studies analysis to assess the effectiveness of these visuals in both conveying climate data and sparking a curiosity in the audience. Despite these limitations, this framework provides a means of incorporating a wide range of geological and/or climate data into generative art which can be integrated into digital and interactive formats for the purpose of science communication.

Disclosures

The authors acknowledge that no known conflicts of interest exist at this time

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