“Sonification of Climate Change: Environmental Data in Sound”

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ABSTRACT

Climate change is an increasingly prominent topic in our daily lives. Both scientists and artists work to inform the public about its consequences and raise awareness by analyzing long-term environmental records and advocating for new habits to mitigate climate change. While this data is often presented visually through graphs, some artists prefer to render it as audio material to better highlight the contrasts, making the changes easier to perceive and, consequently, raising awareness more effectively. However, is this technique used solely to raise awareness, or is it also employed for aesthetic purposes?

This article analyzes three artworks on the topic of climate change to understand how different sound artists present their projects, generating sonifications of environmental data. It compares the various records processed and explains the techniques used to render and map this information. Additionally, an overview of the final results of each artwork is provided.

AWARENESS AND AESTHETICS

Sonification has a wide range of applications, from medical to artistic contexts, each employing different techniques to convey information to the listener. But what is meant by sonification? As the former ICAD president once described, *"Sonification is the use of non-speech audio to convey information. More specifically, sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation"* [1].

Perceiving data audibly can have numerous benefits. Auditory perception offers advantages in temporal, spatial, amplitude, and frequency resolution, providing an effective alternative or complement to visualization techniques [2]. A clear example is the sonification of cardiac signals, particularly the electrocardiogram [3]. This technique allows doctors and nurses to monitor patients while performing other tasks. Additionally, the human auditory system's superior ability to recognize temporal changes and patterns enables artists and scientists to present information that is difficult to understand visually, such as climate change. Climate data, consisting of long-term environmental records, often has minimal impact on a small scale. A common example of climate change sonification is mapping atmospheric CO2 concentration to the pitch of a tone, where the pitch shifts as CO2 levels change, while temperature averages are represented by a ping-pong sound [4]. Listening to sonified data helps individuals perceive the extended temporal relationships inherent in climate data, thereby creating greater awareness of the phenomenon.

Artists also use sonification for aesthetic purposes. In *[Equation]*, Aphex Twin [5] used an early Mac synth program called MetaSynth to convert images to sound, sonifying an image of his face. When the track is played through a spectrogram, his face unexpectedly appears near the end. These methods offer artists opportunities to explore new creative ways to express themselves and surprise the audience, as many techniques remain to be explored.

Paul Vickers introduces the concept of sonification as a series of techniques that use sound for both aesthetic experiences and scientific research [6]. He categorizes these techniques into listening modes based on Pierre Schaeffer's *"quatre écoutes"* [7]. The "reduced" listening mode is suited for scientific exploration due to its focus on sound quality, while the "semantic" and "causal" modes are more applicable for aesthetic purposes.

MAPPING: METHODS AND ATRIBUTES

A wide variety of sonification methods are available. *The Sonification Handbook*, edited by Thomas Hermann, Andy Hunt, and John Neuhoff, provides a comprehensive overview of these techniques [8]. Typically, sonification begins with associating the frequency (pitch)—the primary physical parameter of sound—with the main parameter of the data being represented. Additional data attributes can be mapped to other sound parameters such as timbre, rhythm, and harmony. More complex mapping techniques are increasingly being developed, driven by advancements in technology. For example, data sonification is used for real-time sound spatialization in interactive performances. In the *Room V* interactive sound installation [9], listener motion is captured in real-time using a software interface created with Max/MSP and SoftVNS, and is mapped to the spatialization of recorded acoustic sounds to create a musical composition. The listener's position is interpreted as axis values and associated with various sound attributes, creating an immersive sense of physical reality.

Sonification can be achieved through both digital processes and human interpretation. In *Climate Symphony* [10], an orchestra interprets various environmental records to create a musical composition. The records used include Arctic sea ice extent, NOAA CO2 measurements, floods in Pakistan, and migrant routes across the Mediterranean. Similar to Leah Borromeo's approach, many artists are increasingly exploring diverse environmental records to represent climate change in their work. While CO2 is a common parameter in sonification projects, other factors that directly affect climate change are often overlooked by audiences. Additional projects that utilize different environmental records are presented and analyzed in detail below.

The use of environmental data is not necessarily limited to climate change. In the early 1970s, R. Murray Schafer founded the World Soundscape Project (WSP) and introduced the concept of "acoustic ecology" [11], a discipline that explores the relationship between humans and their environment through sound. Following this initiative, the World Forum for Acoustic Ecology (WFAE) was established, providing online resources for music and sound art projects related to the natural environment. Since then, various artistic projects have been presented.

In 2016, Ruth Jarman and Joe Gerhardt presented *Earthworks* [12], an audiovisual installation that immerses viewers in the phenomena of landscape formation through soundscapes of earthquake, volcanic, glacial, and human activity, recorded as seismic waves and rendered as strikingly fluctuating marbled waveforms. In 1970, Charles Dodge composed *Earth's Magnetic Field: Realizations in Computer Electronic Sounds*, mapping magnetic field data to various sound attributes such as pitch and rhythm [13]. Although these projects are not directly related to climate change, they provide valuable insight into the relationship between artists and their environments.

INTERDISCIPLINARITY AND SONIFICATION

As previously mentioned, sonification can serve various purposes and can be utilized across different artistic disciplines. An example of this is the multimedia dance performance *The Locust Wrath*, where dance is the central focus. Permagnus Lindborg developed software for the interactive sonification of climate data, employing an open-ended approach to parameter mapping that allows for adjustment and improvisation during rehearsals. This results in a broad range of musical expressions [14]

Permagnus began with the goal of creating understandable instruments and maintaining musical integrity to effectively communicate with the dancers. In sonification, such clarity *"pushes listeners toward reduced listening and allows them to grasp the reality portrayed in the data."* The sonification designer collaborated with climate researcher Liong Shie-Yui and his team at the Tropical Marine Science Institute, analyzing two sets of data. They compared long-term environmental changes by measuring humidity, temperature, wind speed, precipitation, and atmospheric pressure using records from 1961 to 2000 across a 352-point lattice in Southeast Asia, as well as predictions for 2081-2100.

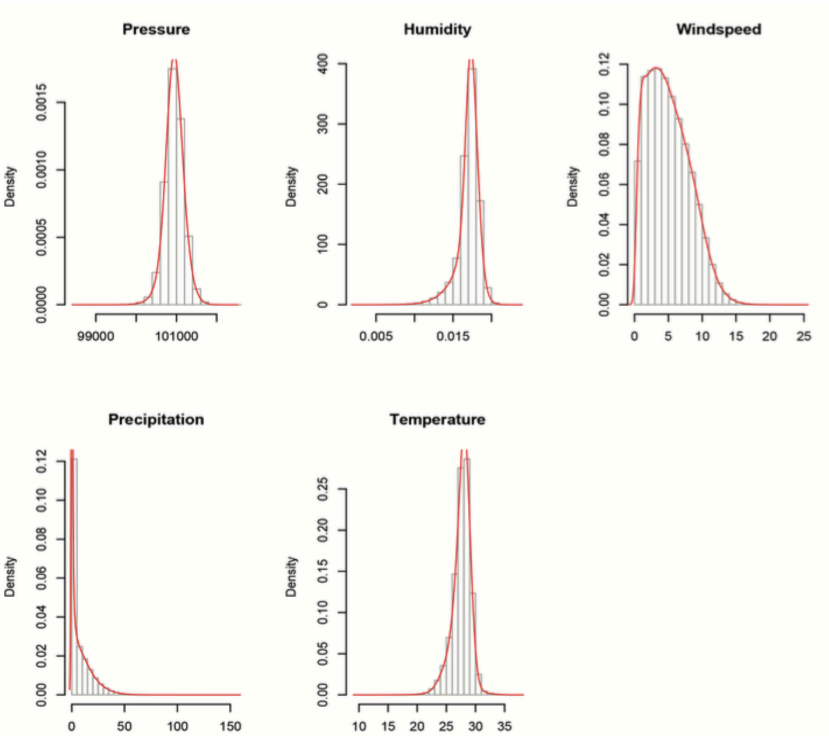

Fig. 1. Histograms of meteorological records used in Locus Wrath.

To develop the sonification method, Permagnus followed the idea of differentiate between "first-order" and "second-order" sonification. The first one is understood as *"the direct linkage between data and sonic rendering"* and the second one as *"the definition of algorithmic processes driven by clusters within the data"*. The initial intention from the *Locus Wrath* team was to apply the principles of sonification as Audification [15], where the time proportions of the underlying data are strictly maintained, assigning 140 years of environmental information to the duration of the piece. Afterwards they realized that using this temporal association was causing fairly neutral perceptual variation in time, generating insignificant dramatic feelings in the piece. In consequence, they decided to generate two main different tempos on the performance. The introduction, a slow-rate (0.45 Hz) audification from a specific period of time from 1965 and the Epilogue, a fast-rate (10.6 Hz) from predicted data from 2091 to 2099, leaving the sections in between with intermediary flow rates, available to adjust according compositional needs.

To develop the sonification method, Permagnus differentiated between "first-order" and "second-order" sonification. The former refers to *"the direct linkage between data and sonic rendering,"* while the latter involves *"the definition of algorithmic processes driven by clusters within the data."* The initial intention of the *Locust Wrath* team was to apply the principles of Audification [15], where the time proportions of the underlying data are strictly maintained, assigning 140 years of environmental information to the duration of the piece. They later found that this temporal association resulted in relatively neutral perceptual variation over time, which generated minimal dramatic effect. Consequently, they decided to implement two main tempos in the performance: a slow-rate (0.45 Hz) audification for a specific period from 1965, and a fast-rate (10.6 Hz) for predicted data from 2091 to 2099, with intermediary flow rates for sections in between, adjustable according to compositional needs.

To understand the mapping method, Permagnus refers to a chapter in *The Sonification Handbook* [16], which presents the mapping system as divided into two parts. **Linkages** involve specifying which perceptual sonic dimensions correspond to given physical dimensions represented in the data. **Transformations** involve defining the functions and input-output ranges for each linkage. The relationship between the climate records and the sound attributes in the piece is categorized into three levels of importance, following Tuuri's "experiential" modes [17]:

Precipitation is linked to pluck, and pressure is linked to detuning, based on the idea that the auditory system's primary task is to alert for potential immediate dangers.

The geographical lattice is connected to spatialization and tessitura, representing the second level of importance. Here, the auditory system seeks to locate the sound source, with the artist using surround sound techniques.

Temperature is linked to resonance, humidity to vibrato, and depth and wind speed to sharpness. This represents the third and final level of experiential listening, reflecting the notion that our perception is connotative and associates sounds with emotions and feelings. For example, a rainfall might affect a specific string at a particular moment in the piece.

SONIFICATION OF CHAOTIC EVENTS

Many factors directly affect climate change, leading to new weather anomalies. Typically, sonification designers compare environmental records along a chronological line to represent these changes. However, another approach is to represent weather irregularities by sonifying specific events. Andrea Polli, a sound artist with over 10 years of experience researching new sonification techniques, has explored this approach. Inspired by the concept of "storm chasing" [18], Polli created a series of multi-channel sonifications of chaotic events, including two historical storms, a tropical hurricane, and a winter snowstorm. The project, titled *Atmospherics/Weather Works* [19], aims to present the audience with an immersive experience of these events and their direct environmental impacts. The project's main goals include: *"the development of a software system for the creation of sonifications based on storm data to be used in performances and installations, live and recorded musical performances, and a web site for the presentation and distribution of the recordings with an interactive interface for listening to the sonifications."*

The first public installation in this series, focusing on recreating "Hurricane Bob" and the "President's Day Snowstorm," was presented at *Engine 27*, a New York organization specializing in multi-channel sound works. Andrea Polli used a 15-channel sound installation to recreate these storms, with each speaker mapped to a specific latitude and longitude in the Eastern United States.

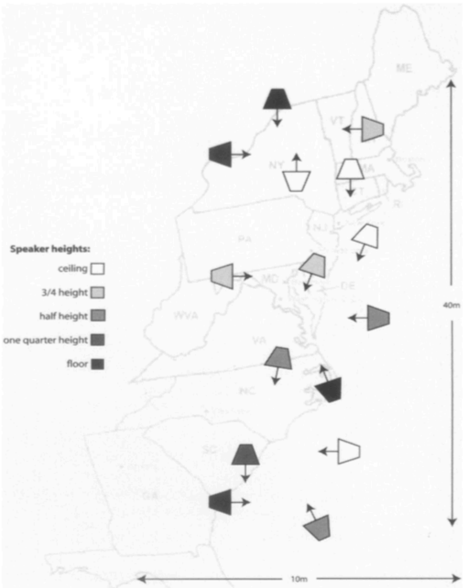

Fig.2. Speakers distribution from *Atmospherics/Weathers Works*

To recreate an accurate model of the storm, six variables were defined: atmospheric pressure, water vapor, relative humidity, dew point, temperature, and total wind speed. To represent the storm's altitude, Andrea and her collaborator Van Kowe divided the space into five different elevation points and assigned them to the various speaker positions (see Fig.2). After modeling the storm, a MAX/MSP system was developed to translate all the analyzed information and spatialize the sound.

Each of the variables was mapped to the pitch of a sound sample, with long tones used for temperature and pressure, and percussive tones for water-related variables. Since some variables were correlated, such as humidity and water vapor, one was assigned as an overall pitch and the other as a filter. To simulate storm activity, a direct mapping between loudness and wind speed was applied to each speaker, generating *"the most sonic activity and excitement."*

INTERACTIVITY AND CLIMATE CHANGE

Until now, most sonification projects have used computer-generated sound to represent data, with the exception of *Climate Symphony* [20], which employed an orchestra. In 2015, *Klima|Anlaga* was exhibited for the first time. This walk-in sound installation, created by a group of artists and researchers, uses four physical sound generators that are electro-mechanically excited and amplified based on environmental record attributes [21]. At this point, there were no longer limitations on working with sonification; humans, computers, or a combination of both could interpret and generate any type of environmental data.

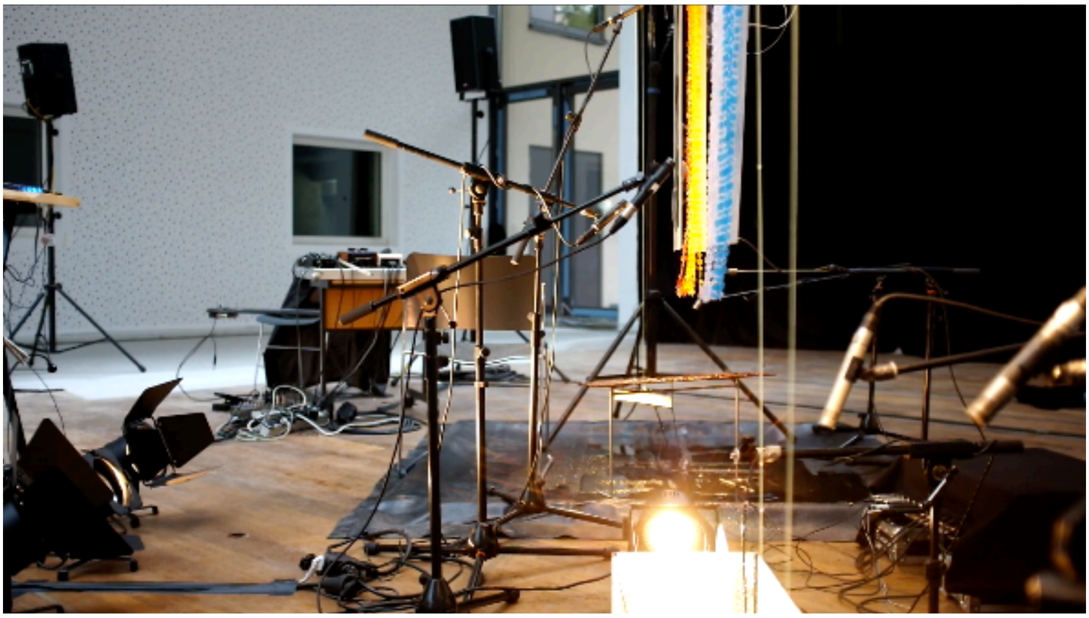

Fig. 3. *Klima|Anlaga set up.*

To represent climate change in *Klima|Anlaga*, the creators chose to sonify two data sets: one related to past and future greenhouse gas (GHG) concentrations and another focusing on past and future environmental properties, including wind, temperature, radiation, and precipitation. Although climate change and global warming involve numerous parameters, the authors opted for parameters that are more readily accessible to human perception. Additionally, the relatively constant incoming solar radiation was included as global annual means.

In the installation, a graphical user interface is presented on a touchpad display, allowing the audience to select and interact with twelve different regions based on the

Fourth Assessment Report of the IPCC [22]. These regions include Agadez (Sahara), Graz (Southern Europe Mediterranean), Berlin (Northern Europe), Johannesburg (Southern Africa), Lhasa (Tibetan Plateau), Jakarta (Southeast Asia), Canberra (Southern Australia), Almaty (Central Asia), Nuuk (East Canada, Greenland, and Iceland), Montreal (East Canada, Greenland, and Iceland), San Francisco (Western North America), and Manaus (Tropics). Each region represents a different climate zone, enabling listeners to compare environmental differences between various geographical areas.

One year of climate records was mapped to 6 seconds of the piece. With this system, a month of data was represented in half a second, resulting in a total composition length of 15 minutes. This approach allowed the audience to perceive the differences between each month psychoacoustically [23], and the overall playing time was suitable for a public exhibition.

The sound synthesis was primarily achieved with physical/acoustical instruments, and each instrument's visual appearance, excitation mode, and materials were related to the data it represented. Precipitation data was depicted using drip devices, including one placed in an aquarium filled with water and recorded with a hydrophone. Wind data sonification was created with a record player turning two marble disks—thicker for higher atmospheric levels and thinner for lower levels. This technique, where conventional devices are repurposed to create new sounds, is known as crack media. For instance, Nam June Paik's 1963 installation *Random Access* allowed the audience to interact with various modified technological devices, such as record players, radios, and phonographs [24]. Temperature data was represented by three metal plates suspended from a large stand, excited by transducers at their resonant frequencies. A monochord [25] was used to simulate radiation data, with electromagnetic drivers exciting the strings individually. Greenhouse gas emissions were represented by a synthesized “beep,” with the sound rate varying according to the concentrations.

CONCLUSION

It is fascinating to observe how sonification is integrated into an interdisciplinary performance like *Locust Wrath*, where sound designers, dancers, directors, and the entire team must understand and harmonize the sonification process and methods. The dramaturgy of the piece must be coherent, requiring the team to collaborate creatively to give meaning to the sonification. In this project, the goal was to create a dramatic experience that conveys climate change to the audience. However, the environmental records used are complex and not directly correlative, making them challenging to interpret. Consequently, the director and team of *Locust Wrath* aimed to raise awareness of climate change through an emotional experience rather than a literal representation of the data.

Atmospheric/Weather works focuses on chaotic events caused by environmental anomalies and illustrates the impacts of climate change in the New York region. The artist aims to recreate these chaotic events with high precision, creating a dramatic and tragic atmosphere for the audience. Despite evoking strong emotions, the installation does not directly raise awareness about climate change. For instance, one audience member found the experience overwhelming and began to cry during the Hurricane Bob sonification. She revealed that she had been caught at sea during the hurricane and that listening to the sonification had resurfaced her traumatic memories. As a result, while the composition elicits emotional responses, it is perceived by the audience as an experience tied to a specific event rather than a broader commentary on climate change.

In a project like *Klima|Anlaga*, where the audience can compare climate change across different geographical areas and the sonification is achieved with instruments closely aligned with the data they represent, the awareness of climate change is significantly heightened. The installation effectively contextualizes the listener by clearly linking sound attributes to the environmental data. Additionally, the interactive display featuring a world map allows the audience to select various cities, facilitating an easy comparison and understanding of climate change effects across different regions.

In conclusion, there are numerous methods to sonify environmental data related to climate change, each with the potential to raise awareness among listeners. However, it is crucial to contextualize the piece for the audience, explaining how the records are represented and how they are associated with the sounds. Moreover, focusing on evoking emotions and feelings can enhance the impact and effectiveness of the climate change awareness generated through sonification.

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