Listening to Earth: Experiments in the Sonification of Climate and Environmental Data

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Abstract

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Climate change is a geologic event in which we are both witnesses and participants. It defies straightforward categorization yet increasingly alters daily life and poses an existential threat to species around the world. And so there is an urgent need for transdisciplinary approaches to promote collective understanding of the staggering changes that are recorded in, and predicted by, environmental data. This document outlines a multi-year creative experiment making music compositions with climate data from ice cores, weather stations, and satellites. These

compositions have been performed for live audiences, played on public radio stations in multiple countries, displayed in museum exhibits, and discussed in popular media articles. This dissertation surveys the theory and practice of data sonification, situates environmental data sonification in historical context, and describes the collection of compositions made from environmental data: the process, techniques and outcomes.

Part I of the dissertation, chapters 1 - 3, gives an introduction and orientation to the body of work. Chapter two provides historical context and situates the global network of climate data monitoring sites within its tangled history of colonialism, by outlining two threads in the development of meteorology in Britain and the United States. Chapter three describes features and methods of sonification, and describes a range of environmental sonifications by contemporary sound artists and scientists, to show the breadth of this interdisciplinary approach to environmental communication.

Part II of the dissertation, chapters 4 - 7, describes the extant collection of sonifications that comprise this multi-year experiment: documenting the intentions, methods, composition process, and performances of the different sonifications. Each chapter focuses on a different set of compositions. Chapter four outlines three early works which I composed after completing a masters degree in Atmospheric Sciences and prior to studying digital sound synthesis. These digital pieces are a sonification of the Keeling Curve, documenting the concentration of atmospheric carbon dioxide, a sonification of the record of global mean surface temperature, and a sonification of Arctic sea ice. Chapter five presents an acoustic composition and score of the satellite record of Arctic Sea Ice written for piano. I describe the process and structure of this composition, as well as the youth-led workshop which this piece inspired. Chapter six outlines a multi-artist, multimedia project which blends environmental health data with recordings of human breath and interviews, as part of an exhibition called “Breathing in a Time of Disaster.” Chapter seven presents the *Timescales Collection*, a four-piece collection which sonifies the record of atmospheric carbon dioxide on multiple different timescales, spanning weeks to hundreds of thousands of years, showing the different layers of change that is recorded in this geologic record. The concluding chapter reflects on the role that the musical expression of climate data can play in our emerging understanding of this new planetary age.

Acknowledgements

I could not have done this work without the support of many individuals and communities.

My advisor and committee chair, Professor Dargan Frierson, has shown unwavering support for this project from the very beginning. Without his enthusiasm for my initial experiment in data sonification, I would never have pursued, or completed, this project. I also wish to thank Professor Cecilia Bitz, whose wise and candid counsel and dedication to polar climate research inspired my interest in Arctic climate data, and the sonifications that followed. When I decided to branch away from research in climate science and pursue an individualized Ph.D. program in climate data sonification, Professor Juan Pampin welcomed me into the department of Digital Art and Experimental Media, offered invaluable feedback, and connected me with networks of sound artists I wouldn't otherwise have known. Professor Esther Min generously agreed to join my committee in the final year, when I decided to make environmental justice more explicit in this work. Thank you for your feedback especially on chapters two and six. I also want to thank faculty members outside my committee who helped me navigate this journey: Luanne Thompson, who mentored me in decisions about choosing graduate programs, and Joseph Anderson, who taught me about digital sound synthesis and composing in SuperCollider.

In addition to my academic committee, I was fortunate to have a community reading committee of colleagues who are familiar with my work but are not experts in digital music or climate science. Their feedback on chapters and ideas was extremely helpful. I thank Kathy Egawa, Doung Than, Sarah Inman, Rachael Osborn, and Jeremy Bendik-Keymer.

The piano composition *Arctic Sea Ice (2018)* would not have come together without the invitation from the TEDxSeattle Community, and my wonderful collaboration with pianist Kristina Lee.

My sangha on Vashon Island, *The Puget Sound Zen Center*, helped me find a stable center in difficult times, brought us food when my whole family was sick, and taught me new ways of listening.

I also wish to thank my partner Dustin Lundquist for steadfast friendship and support, and my mom Gretchen Nielson, who lovingly cared for my toddler in the last year of this project.

This work is dedicated to Matilda Mae Orion.
In your own way, you inspired me to finish this project.

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Chapter 1. Introduction

Motivations

Over the period that I have worked on this dissertation, public recognition of the climate crisis has shifted. In 2019, young people around the world entered a state of open rebellion against the physical and political infrastructure that puts their future, and the prospects of a liveable planet, in jeopardy. Students from primary school on up, around the globe, went on strike, organized protests, and wrote books[1] to educate others and motivate climate action. The Yale Program on Climate Change Communication has surveyed American beliefs and behaviors about climate change starting in 2008[2], and their results show that the percentage of adults who are aware of the scientific consensus around global warming has increased from its lowest point in 2010 – just 33% of all Americans – to well over half of American adults in 2022. And more than two thirds of American adults believe that climate change is happening (see figure 1.1).

[1] See, for example, "Youth to Power" by Jamie Margolin (Hatchett Books, 2020), "A Bigger Picture: My Fight to Bring a New African Voice to the Climate Crisis," by Vanessa Nakate (Mariner Books, 2021), and "The Climate Book" by Greta Thunberg (Penguin Press, 2023).
[2] Yale Program on Climate Change Communication (YPCCC) & George Mason University Center for Climate Change Communication (Mason 4C). (2022). *Climate Change in the American Mind: National survey data on public opinion (2008-2022)* . doi: 10.17605/OSF.IO/JW79P

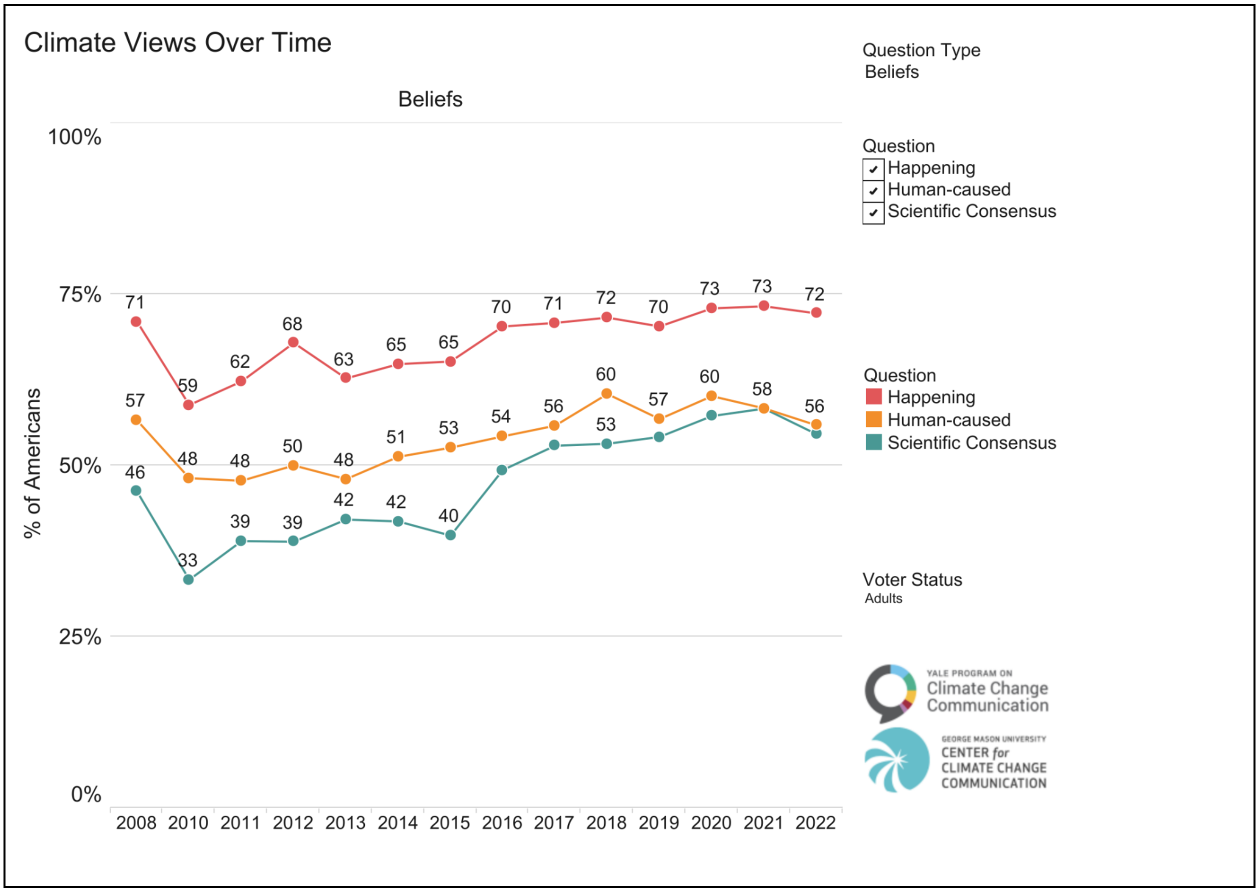

Figure 1.1 Adult American views about climate change, from 2008 - 2022.

One of the results of their survey, which motivated this experiment in data sonification, was a question about behaviors. When asked "How often do you discuss global warming with your friends and family?" only a third of American adults answered "often" or "occasionally." *Despite increasing recognition that global warming is happening, it is human caused, and that it is consensus science, still the majority of American adults rarely if ever talk about it.* This may be linked to the follow up question, which was "How often do you hear about global warming in the media?" Figure 1.2 shows that the percent of adults who answered "at least once a week" has remained below 33%, although it reached a peak in 2019, the year of the global student climate strikes. And while this is only a survey of American opinions and behaviors, other studies have found similar results in different countries. For example, Kari Norgaard, a sociologist whose work is discussed further in chapter three, found a similar lack of discussion of climate change in a rural Norwegian community with a strong cultural ties to outdoor activities.

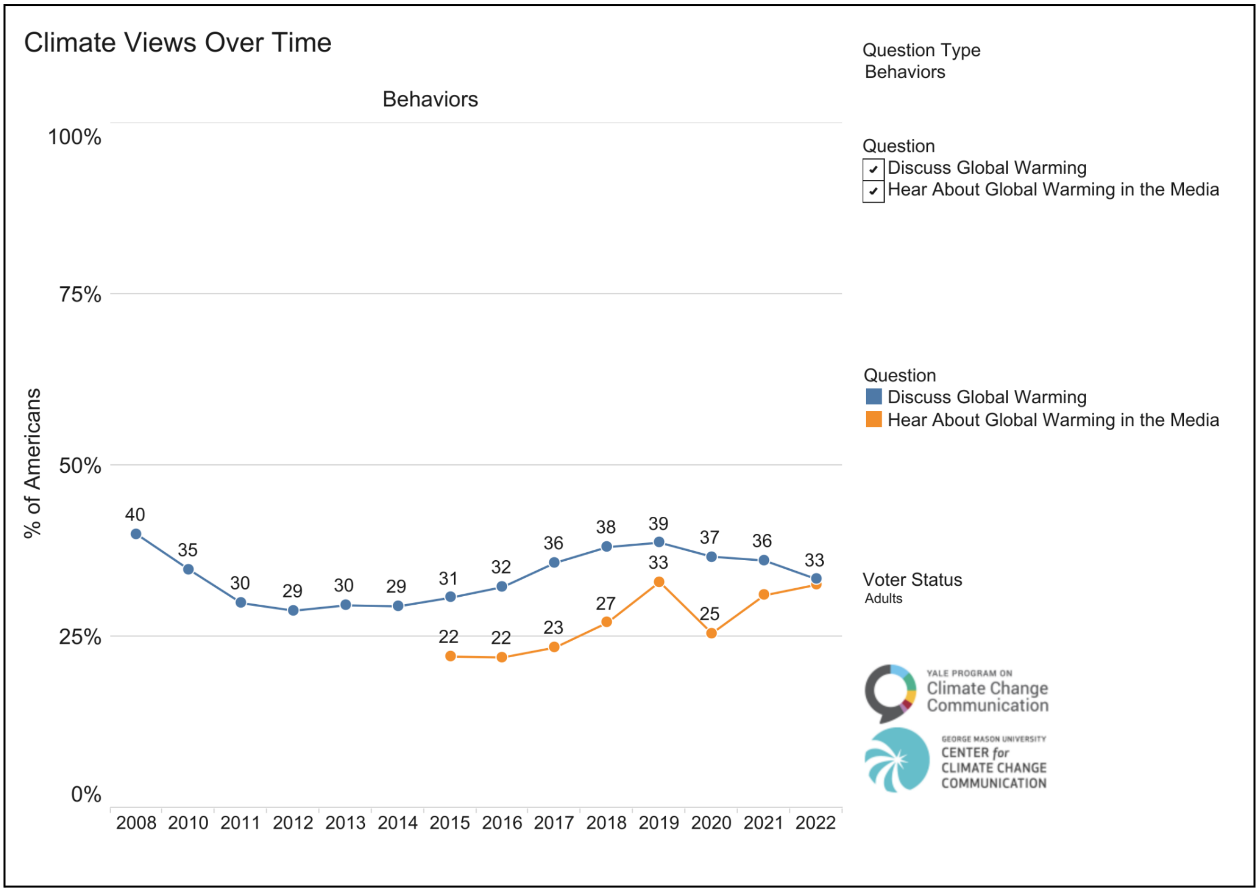

Figure 1.2 Responses of adult Americans who discuss global warming often or occasionally (blue line), and who hear about it at least once a week in the media (orange line).

My work is motivated by a desire to make climate change, and considerations of the planet and biosphere – more salient for ordinary people. And it is guided by the recognition that environmental data is an artifact of a living ecosystem that comes from a site, or many sites, of connection between scientists and the environment. My intention, in creating art with data, is to weave stronger relationships between listeners and living ecosystems. This dissertation is a story about the process and product.

I write in two alternating voices: the chapters are written primarily for an academic audience and because this is interdisciplinary work, I minimize the technical language of specialized disciplines. These chapters could stand alone as a traditional dissertation and could be read in series. The interlude sits between the chapters. It describes my experiences and relationships that informed and shaped my work. I thank my friend and undergraduate mentor, Jeremy Bendik-Keyer, for the suggestion that I see my family in this work. And I also thank Shawn Cree, whose beautiful work *Research is Ceremony*, has given me the inspiration to explicitly include my family and extended community in this work. A significant part of that process is developing an understanding of my relationship to the audience when preparing work. My learning in this area was most significantly shaped by experience with the organized labor community in King County.

Outline of the Chapters

Climate science, arising in the 19th and 20th centuries in Western Europe and North America, exists within a culture and history of extraction and colonialism, whereby the relationship between people and land is severed and disregarded. A culture of extraction is characterized by a process in which resources are removed from their environments and webs of relationships, and turned into abstract value or information for consumption. Chapter two provides an historical outline of the development of meteorology and climate science in western Europe and the United States, with emphasis on the acts of white superiority within two institutions of meteorology: the Met Office in London, and the Signal Corps in colonial America. Attitudes of white racial superiority prevailed among the scientists leading the development of this field and influenced or justified methods in environmental data collection as well as attitudes about who does science and how it is done, that still reverberate in labs and universities today. This provides historical-cultural context for the rest of this work, and while not all datasets that I use share this colonial history, this chapter serves as an example of viewing through a broader lens that may ultimately improve the usefulness and accountability of climate and environmental science.

Chapter three then offers a birds-eye view of environmental data sonification and composition. Data sonification is analogous to data visualization. Rather than representing a set of numbers visually in a chart, sonification represents those numbers with sound. We look first at the research around climate communication, expunging the dominant information-deficit model of scientific communication with one that includes human expression and emotion. Then, we look at examples from other sound artists and scientists. This chapter is intended for those curious to understand the technical considerations in this work, and for those who might wish to create sonifications.

Chapters four through six each present a different collection of compositions. For each sound piece, I discuss the source of the data, how the data is mapped to sound properties (called parameter mapping), and the aesthetic choices I made in the composition process. Chapter four presents three early works that were composed prior to my work and training with the Digital Arts and Experimental Media (DXARTS) program. Chapter five presents *Arctic Sea Ice*, an acoustic composition for solo piano that represents the satellite record of sea ice extent over the Arctic Ocean. The compositions in chapters six and seven were created after two years of creative study with colleagues and mentors in DXARTS. Finally, I conclude with reflections on data representation and possible directions for environmental sound art.

Chapter 2. Climate Data Collection and Representation in Historical Context

History is not merely something to be read…the great force of history comes from the fact that we carry it within us, are unconsciously controlled by it in many ways, and history is literally present in all that we do.

-James Baldwin[3]

This dissertation is an experiment in artful science communication, an attempt to express geophysical data in a way that brings listeners into closer relationship with lands and ecosystems from which the data was taken. It's in pursuit of reconnection by way of storytelling without words. Environmental data – mostly data sets of large geographic scale – are the starting point for the compositions, the wordless stories. The data tell a story, and this guides the approach to the composition, but there is another layer of story that precedes the composing process: the story of the data collection. The capacity to measure the global mean surface temperature – one of the key measures of global warming today – depends on a coordinated global monitoring network of weather stations. How, and when, did this network come to be?

The brief history told here started as an investigation into early examples of public-oriented data visualization, when I learned that the first weather map was made by Francis Galton, the founder of eugenics and influential leader in scientific racism. This investigation led me into a period of earth science history that is embedded in the pursuit of racial and colonial domination by influential European and American scientists, a history that may help us understand why the environmental sciences remain the least diverse field among all STEM fields.[4] This history is the topic of entire books. What I wish to do in this chapter is highlight some of the ways in which geophysical data collection and the emergence of meteorology as a discipline happened in tandem with racial domination and the expulsion of Indigenous peoples from their lands. This is the history of institutions who gathered the data that I use in these sonifications, and it offers a

[3] Baldwin, James. "White Man's Guilt," *Ebony Magazine*,(1965)

[4] Bernard, R.E., and Cooperdock, E.H. No Progress on Diversity in 40 years. *Nature Geoscience, 11, 292-295, (*2018)

starting point for reflection on the purposes of geophysical data. The reflections are the subject of the final sections in this chapter.[5]

The majority of compositions in this dissertation use temperature, carbon dioxide, and sea ice data measured through global observing networks run by the National Oceanic and Atmospheric Administration, which was established in 1970 by merging three environmental research agencies – Fisheries, the Coast and Geodetic Survey, and the National Weather Service – into one federal agency within the Department of Commerce. The precursor to the National Weather Service was the Weather Bureau, which was preceded by the U.S. Army Signal Corps during the wars with Indigenous Americans over their lands. The establishment of that Signal Corps's weather monitoring network is one of the two threads woven through this chapter. The other is a story about the cultural impact of the man who published the first weather map and led the development of the British Meteorological Council.

Meteorology Needs Land

> "A scientific study of the weather on a worthy scale, seems to me an impossibility at the present time from want of accessible data. We need meteorographic representations of large areas, as facts to reason upon…"
>
> Francis Galton, 1861[6]

British scientist and explorer Francis Galton was one of the early developers of meteorology in Britain. In his 1861 book *Meteorographica, Or Methods of Mapping the Weather*, Galton noted that meteorology was in need of data from vast tracts of land. Within a few decades, his wish was granted. Over Galton's lifetime, Britain and the United States established such networks of weather stations throughout their expanding colonies, and their histories of meteorology are tightly interwoven.

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[5] The fact that my knowledge of this history was accidental is telling – one can become a specialist in climate science or related fields without ever studying the history of the field.
[6] Galton, Francis F. *Meteorographica, Or Methods of Mapping the Weather.* Macmillan, 1861.

In the United States, westward expansion on Indigenous lands made such a network possible. In an impassioned congressional debate leading up to the narrow passage of the Indian Removal Act Congressman Richard Wilde explicitly linked the march of science to Indian removal: *"Are our sciences, our arts, our literature, our institutions… to be surrendered to the natural claim of the Indian to the forest?"*[7] This act, signed by president Andrew Jackson in 1830, authorized the president to negotiate removal treaties with Indian tribes living east of the Mississippi, and this was only the beginning of westward expansion onto 'the frontier.'[8] During this time, the Army Medical Department carried out observations of air, water, and land to protect the health of the troops.[9]

Between 1860 and 1890, American Indian wars intensified on the lands of Indigenous nations including the Sioux, Crow, Cheyenne, Arapahoe, Pawnee, Blackfeet, Ute, Nez Perce, Navajo, Apache, Modoc, Kiowa, Comanche, and many other. The U.S. military fought, raped, slaughtered and forced native peoples onto reservations while army outposts claimed and colonized western land with settlements, mining, agriculture, and railroad.[10] Coordinated American weather forecasting came after an 1869 act of congress[11] mandated an extensive system of meteorological observations that would serve commerce and agriculture. Onto this network of army outposts, the U.S. Department of War grafted the Signal Corps meteorology program.[12]

The 1872 War Department Report to Congress[13] contained a detailed briefing from the Chief Signal Officer with status of the weather stations and data collected, alongside a report from Lieutenant General Sheridan with recommendations on the the approach to conflict with

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[7] Register of Debates, 21st U.S. Congress, 1st sess p 1083, Richard H. Wilde of Georgia, May 19, 1830.
[8] The Indian Removal Act passed the House of Representatives in a vote of 102 to 97, and passed the Senate in a vote of 28 to 19.
[9] Fleming, James, *Fixing the Sky: The Checkered History of Weather and Climate Control*, Columbia University Press, 2010, p.169
[10] Estes, Nick. *Our History is the Future*, Chapter 3, New York: Verso, 2019.
[11] Miller, E.R. "The Evolution of the Meteorological Institutions in the United States." *Monthly Weather Review,* 59, 1-6, *(1831)*
[12] Fleming, J.R.. Stormes Strikes and Surveillance: The US Army Signal Office 1861 - 1891, *Historical Studies in the Physical and Biological Sciences, 30, 2 (2000)*
[13] Report of the Secretary of War Vol IV: Annual Report of the Chief Signal Officer, (1876) https://hdl.handle.net/2027/uc1.b2979904

Indigenous Nations: *"I fully endorse the efforts now being made to civilize and Christianize the wild indians...if some wise system of punishment could be arranged and carried out which would have the effect of controlling him...it would much sooner terminate the Indian troubles on our frontier."*

During these wars, the army sanctioned the mass slaughter of Buffalo to eliminate a primary food supply and close relative of Plains nations. Indigenous historian Nick Estes observes that unlike the European holocaust, "Indigenous elimination, as a practice and formal policy, continues today, entailing the wholesale destruction of nonhuman relations."[14] Through these wars, the Signal Office expanded the military telegraph lines into lighthouses and mountain stations, and into Indigenous lands in the southwest and northwest frontiers. A special set of telegraph lines allowed signal officers to 'report suspicious activity' by surveilling from military posts near reservations.[15]

By 1879, 73 stations and 5,000 miles of lines stretched from the Dakotas to Washington Territory in the northwest and from Texas to California in the southwest. They served as both military surveillance and weather station outposts while the Federal Government aggressively pursued a mission of expansion. A map of telegraph lines from the office of the Chief Signal Officer shows weather stations on the telegraph network intruding into Indian Territory (figure 1.1).

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[14] Estes, 2019.
[15] Fleming, 2000.

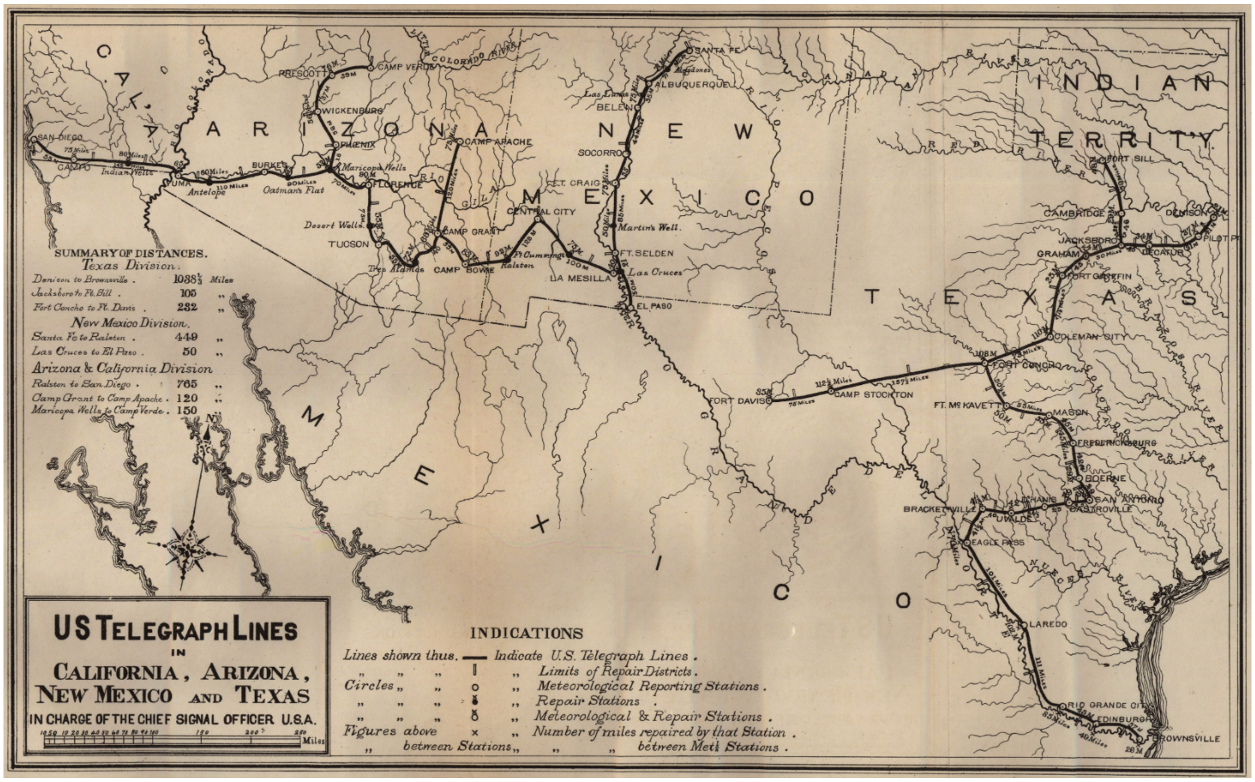

Figure 2.1 1879 Map of US Telegraph Lines and Meteorological Stations from the office of the Chief Signal officer during the era known to the US military as the Indian Wars.

In less than a century, the US annexed over two billion acres of Indigenous territory.[16] Only after decades of war and land theft did Congress move the meteorological work of the Signal Office to the newly formed U.S. Weather Bureau under the Department of Agriculture,[17] in 1892. With this extensive network of weather data, new organizations and scientific societies formed, including the New England Meteorological Society, the Blue Hill Meteorological Observatory, and the American Meteorological Journal.[18] This nascent assemblage of meteorological institutions laid the foundation for modern American weather and climate research. And although the Weather Bureau became a civilian office, connections between the military and meteorology continued to

[16] Estes, 2019.
[17] Coker, K. & Rios, C. A Concise History of the US Army Signal Corps, *Office of the Command Historian*, U.S. Army Signal Center and Fort Gorton, 1988. https://apps.dtic.mil/dtic/tr/fulltext/u2/a208887.pdf, accessed 5/6/2023.
[18] Conover, J. "Highlights and History of the Blue Hill Observatory and the Early Days of American Meteorological Society", *BAMS*, 6,1, 1985.

grow. Almost a decade after World War II, a National Science Foundation survey of professional meteorologists found that 80% had ties to the military through Air Force Reserve, Navy Reserve, or in active duty.[19]

Scientific Racism

British weather research developed alongside its American counterpart, and was heavily influenced by one of the early American proponents of weather forecasting, Navy Officer Matthew Maury. He led the US Navy's Depot of Charts and Instruments as the British Empire was outfitting colonies with research stations for weather prediction, and Maury was gaining international attention for his charting which aided ocean navigation. Since international trade was accomplished primarily through shipping, nautical weather prediction and navigational charting was especially valuable. In Britain, lack of systematic coordination or standardization greatly reduced the usefulness of their observation networks.[20,21] Maury was just the man to help them. While head of the Depot of Charts and Instruments, Maury revised charts of the Atlantic, Pacific, and Indian Oceans that greatly reduced navigational passage times. "Before his charts came to be used, the average passage from New York to San Francisco was about 180 days, but by the year 1855 the average passage between those ports for the year round was reduced to 133 days."[22] In 1851, Maury received an invitation from British Army Officer William Reid to expand and improve the British meteorology network through American collaboration. Maury accepted, and coordinated an international meteorological conference in Brussels in the summer of 1853**.** The conference established an international code of observational practice at sea, including the use of a standard meteorological register for recording observations, and led to the creation of the British Meteorological Office, today referred to simply as the 'Met Office.'

It was common for natural scientists like Maury to discuss racism as a 'science' that justified racial domination. Archives from the third meeting of the American Association for the

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[19] Fleming, 2010.
[20] Walker, J.M. *History of the Meteorological Office*. Cambridge: Cambridge University Press https://doi.org/10.1017/CBO9781139020831 (2011).
[21] Fleming, J.R., *Historical Perspectives on Climate Change,* New York: Oxford University Press, 1998.
[22] Lewis, C. L., *Matthew Fontaine Maury: the pathfinder of the seas*. Annapolis, United States Naval Institute, 1927, https://www.gutenberg.org/files/65071/65071-h/65071-h.htm, accessed 5/6/2023.

Advancement of Science included talks by Maury on "The General Circulation of the Atmosphere" alongside talks on "Examination on the Physical History of the Jews" and "Physical Characteristics of the Hindoo Skull."[23] Maury also equated the rise of science with political conquest. In an 1853 petition to persuade the US Congress[24] to open the Amazon River to American navigation so that southern states could sell off the enslaved and 'get clear of them,' Maury described a Navy officer dispatched to the Amazon on a reconnaissance mission: "In obedience to the humane and enlightened spirit of the age, which calls upon science, commerce, and navigation, not upon arms, for conquest..." Retiring from the Naval Observatory in 1861, he moved back to Virginia and worked on behalf of the Confederacy, establishing a network of submarine mines and petitioning France to recognize the confederacy. Today he is remembered as the 'father of oceanography.`[25]

Maury's contribution to the establishment of the British Meteorological office was not in vain. In 1865, the British Board of Trade appointed Francis Galton to review and make recommendations for the further development of the Meteorological Office. Galton was president of the British Association for the Advancement of Science, led research in heredity and eugenics and was a cousin of Charles Darwin.[26] Inheritance from family fortunes made in banking and gun manufacturing allowed Galton to travel on African safaris and experiment in a range of scientific endeavors. Under Galton's leadership, the committee made new recommendations for the structure and operations of the Met Office in a document known as "The Galton Report." Among the outcomes of the Galton Report was a restructured Met Office under the Royal Society, with an eight-member oversight committee[27, 28] upon which Galton sat until just before his death in 1911.

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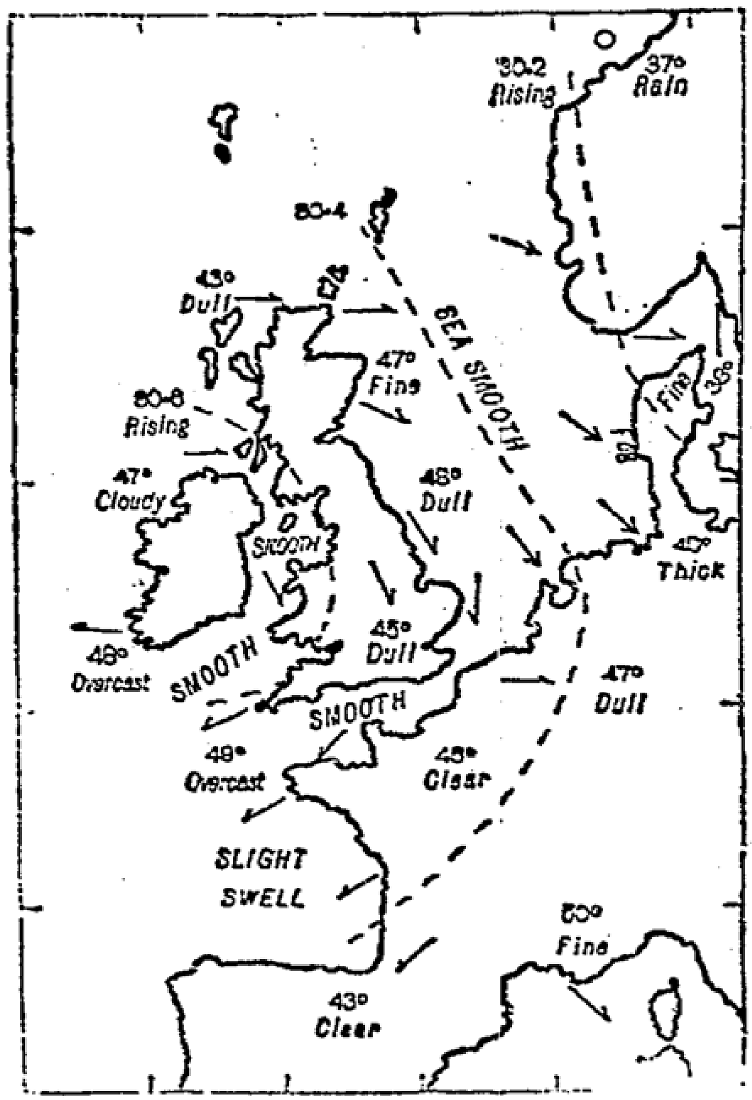
[23] Proceedings of the American Association for the Advancement of Science, Charleston: Liberality of the Corporation of Charleston (1850), https://hdl.handle.net/2027/hvd.tz17kt , accessed 5/6/2023.
[24] Lewis, 1927.
[25] See, for example: Marshall, John and Alan Plumb, *Atmosphere, Ocean, and Climate Dynamics: an introductory text*, Elsevier, 2008, a common undergraduate textbook in climate science.
[26] Walker, J.M. *History of the Meteorological Office*. Cambridge: Cambridge University Press https://doi.org/10.1017/CBO9781139020831 (2011).
[27] Walker, 2011.
[28] British Parliament, Report of a Committee Relating to the Meteorological Department of the Board of Trade, 1866, London: Archives of the University College of London Galton Papers.

WEATHER CHART, MARCH 31, 1875.



The dotted lines indicate the gradations of barometric pressure The variations of the temperature are marked by figures, the state of the sea and sky by descriptive words, and the direction of the wind by arrows—barbed and feathered according to its force. ⊙ denotes calm.

Figure 2.2 Galton's 1875 Weather Map, the first of its kind, published in the London Times while he supervised the Met Office.

A man of many interests, Galton published books on geography from his experience in African Safaris, and wrote extensively about heredity and eugenics. While chairing the committee review of the Met Office, Galton published a *Hereditary Talent and Character*[29], just six years after his cousin Charles Darwin released *The Origin of Species*. The opening statement declares "the power of man over animal, in producing whatever varieties of form he pleases, is enormously great. It would seem as though the physical structure of future generations was almost as plastic as clay, under the control of the breeder's will."

During this period, Galton continued to publish methods in statistics and weather predictions, but his primary interest was promoting a vision and method of racial progress through genetic 'purification' that would be 'introduced into the national conscience, like a new religion,' because, "*what nature does blindly, slowly, and ruthlessly, man may do providently, quickly, and kindly."*[30] *Hereditary Genius*, which he published in 1869, proposes "to show that a man's natural abilities are derived by inheritance.' It included a chapter on the "The Comparative Worth of Different Races" where Galton introduced the concept of statistical regression, now ubiquitous in science, to argue that mental and physical traits regress toward a racial center.

This work was influential to many scientists of the day, including his protegé Karl Pearson and his cousin Charles Darwin. As Darwin's theory of evolution gained acceptance, he lent his reputation to support Galton's work. In Darwin's less-remembered second book, *The Descent of Man* published amidst the U.S. appropriation of Indigenous land across the plains, Darwin quoted Galton's "Hereditary Genius" frequently, and drew from his theory of natural selection to justify colonial expansion as the progress of civilization and perfection of the white race:

"In all civilised countries man accumulates property and bequeaths it to his children. So that the children in the same country do not by any means start fair in the race for success. But this is far from an unmixed evil; for without the accumulation of capital the arts could not progress; and it is chiefly through their power that the civilised races have extended, and are now everywhere extending their range, so as to take the place of the lower races."

[29] Galton, F. Hereditary Talent and Character Pt I. (1865), London: Macmillams Magazine http://galton.org/essays/1860-1869/galton-1865-her-tal-1-upgrade.pdf
[30] Galton, Francis, "Eugenics. Its definition, scope, and aims." *Nature,* 69, 294-5, (1904), accessed 4/18/2023 at https://galton.org/essays/1900-1911/galton-1904-eugenics.pdf

Darwin's support for Galton's work was a tacit endorsement of both race replacement and class superiority. Darwin's family names also show the familial esteem for Galton: Darwin's grandson, who later became the director of the National Physics Laboratory, was named Charles Galton Darwin and his great grand-son was Henry Galton Darwin.

In 1874, while enjoying support among many scientific elites, Galton articulated a relationship between men of science and white male cultural status in his work "English Men of Science " in which he aimed to discover a "natural history of the English men of science." Building on *Hereditary Genius,* he started by identifying the 'hereditary influences' and 'inborn qualities of mind and body' of English scientists through sociological survey. Among the many conclusions was that *"There can be no doubt but that the upper classes of a nation like our own, which are largely and continually recruited by selections from below, are by far the most productive of natural ability. The lower classes are, in truth, the 'residuum'."* One year later, Galton published the first weather map in the London Times in 1875 (figure 2.2), while continuing his supervisory role in the Met Office.

Galton died shortly after he retired from the meteorological council and left a burgeoning eugenics movement in his wake. He bequeathed £45,000 to found the Laboratory of National Eugenics.[31] His student Karl Pearson received Galton's endowment of the Galton Chair of Eugenics at the University College, London. In 1912 the British Medical Journal printed proceedings from the First International Conference on Eugenics, organized by Charles Darwin's son and chairman of the British Eugenics Society. By then, eugenics was deeply rooted in the United States: a report from the American Breeders Association described surgical procedures for males and females of 'eight of the states in the union where there are laws authorizing or requiring sterilization of certain classes of degenerates and defectives'. In the United States philanthropists eagerly supported the eugenics effort. Foundations including Kellogg, Carnegie, Rockefeller, and the Harriman Railroad fortune funded research, conferences, and social programs in eugenics. Harry Laughlin who led the eugenics records office in New York with support from the Carnegie Foundation, developed pedigree charts to identify the 'socially

[31] H., T. The Galton Bequest. *Nature* 86, 92, (1911). https://doi.org/10.1038/086092a0.

inadequate' and drafted model sterilization laws. In 1907 Indiana became the first state to enact compulsory sterilization laws; 29 more states would follow, and in 1924 Virginia passed the Racial Integrity Act, which made it illegal for Virginians to marry outside of their race. In the U.S., many of these laws remained in effect with active state support throughout the 1970s. California performed more involuntary sterilizations than any other state, the practice continued through the late 1970s. Across the country as many as 70,000 people -- primarily poor, Black, Indigenous and/or disabled women were forcefully sterilized.

In this culture of scientific racism and quest to control the future, atmosphere and ocean sciences grew. For meteorology in the United States, the outcome of the Indian wars and land theft was a transcontinental network of weather stations[32,33] upon which it advanced into the 20th century. In 1902 the Carnegie Institution of Washington, a major academic research center, listed among its goals, ``to discover the exceptional man in every department of study whenever and wherever found, inside or outside of schools, and to enable him to make the work for which he seems specially designed..."[34] Cleveland Abbe, chair of the Carnegie Advisory Committee on Meteorology, argued in his request for funding that "meteorology had attained status equal to astronomy in the century between Newton and LaPlace," and that the field presently needed 'mathematicians of the highest genius." Abbe predicted that the most important discoveries would come not from hundreds of experimentalists and thousands of observers, but from "the pre-eminent right man."

One might want to dismiss the valorization of genius and exceptionalism in science as a thing of the past, but it lingers today in common stereotypes of scientists.[35,36,37] A recent study at a diverse US community college asked students how their perceptions of science changed after learning

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32 Miller, 1831.
33 Fleming, 2000.
34 Carnegie Institution of Washington Yearbooks: https://carnegiescience.edu/carnegie-institution-year-books-numbers-1-through-99-years-1902-through-2000, accessed 9/18/2020.
35 Leslie, S.J., Cimpian, A., Meyer, M., & Freeland, F. "Expectations of Brilliance Underlie Gender Distributions Across Academic Disciplines". *Science, 347, 262-265,* 2015.
36 Bian, L., Leslie, S.J., Cimpian, A. "Gender Stereotypes about Intellectual Ability Emerge Early and Influence Children's Interests". *Science, 55(6323) 389-391,* 2017.
37 McGee, E. O. "Devalued Black and Latino racial identities: A by-product of STEM college culture?" *Am. Educ. Res. J.* 53, 1626-1662, 2016.

more about the everyday lives of scientists[38]. One student responded “I used to think scientists were mere geniuses who asked infinite, even unpredictable questions nobody had time to research.” Another noted that before the class she thought scientists were people who “thought they were above everyone else.”

Repurposing Data

I’ve offered a very brief early history of leading American and British weather research, in order to situate the task of understanding climate data within the broader context of understanding the ongoing impacts of colonialism. Obsessions with the classification and control of humans and the environment pervaded Western science and were especially prominent in Francis Galton’s work. Breaking Indigenous people’s ancestral connections to their lands, which facilitated global monitoring networks, created multigenerational trauma. Today, some Indigenous peoples critique framing climate change as a ‘new’ existential threat, or as a crisis of the future. Forced relocation was an experience of environmental change that rivals their contemporary environmental challenges.[39] In the words of historian Deborah Coen, “There is an uncomfortably intimate relationship between the growth of environmental knowledge and the environmental destruction wrought by imperialism,”[40] and similarly, sociologist Kari Norgaard writes that “climate change needs to be understood as the latest intensification of dynamics on a long continuum of colonialism.”[41]

Climate data documents very specific records of change (i.e. time series of temperature, pressure, gas concentrations, etc..) from the locations in which they were taken. When the historical context of data collection is included in consideration of the data, a fuller picture emerges, one

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[38] Schinske, J.N., Perkins, H., Snyder, A., & Wyer, M. “Scientist Spotlight Homework Assignments Shift Students Stereotypes of Scientists and Enhance Science Identity in a Diverse Introductory Course”, *CBE Life Science Education, 15, 741 - 749* (2016).
[39] Whyte, Kyle P, “Indigenous science (fiction) for the Anthropocene: Ancestral Dystopias and fantasies of climate change crisis” Environment and Planning E: Nature and Space, Vol. 1 (1-2) 224-242, 2018).. DOI: 10.1177/2514848618777621
[40] Coen, Deborah, “Climate in Motion: Science, Empire, and the Problem of Scale.” University of Chicago Press, 2018.
[41] Norgaard, Kari. “Salmon & Acorns Feed Our People: Colonialism, Nature, and Social Action.” Rutgers University Press, 2019.

that resists separating process from product. The process matters because it forms, or breaks, relationships among people and the site of collection.

In consideration of this history, I suggest that we view climate change as a symptom of broken relationships with land, air, water, and between people who have fought over them. Today the research which catalogs, explains, and predicts extreme weather and climate change continues to be predominantly white-led, even as Black, Indigenous, and brown communities and countries suffer disproportionately from pollution and high social vulnerability to extreme weather and climate change.[42,43,44,45,46] Furthermore, damages from climate change are primarily calculated by financial means, which prioritizes property over people, and commodifies the natural world.[47] In the 21st century, practical knowledge of environmental science is increasingly a matter of survival for people and communities contending with droughts, wildfires, floods, and other climate disturbances, but avoiding mass extinctions of nonhuman species and reducing massive dislocation of human communities in the coming century will require reparations between humans and the environment and also between countries which have profited from environmental damage and those who have not.[48] A full discussion of climate reparations is outside the scope of this work, but has become a major focus of international climate negotiations due to the efforts of small island nations and developing countries. Reparations on a global scale may seem an unfeasibly large, audacious goal but, as philosopher Olúfẹ́miTáíwò

[42] Schell et al., The Ecological and evolutionary consequences of systemic racism in urban environments, *Science, 369, 6510,* 2020. DOI: 10.1126/science.aay4497
[43] Tessum, et. al. "Inequity in consumption of goods and services adds to racial-ethnic disparities in air pollution exposure" *PNAS, 116, 13,* 2019. *https://doi.org/10.1073/pnas.1818859116*
[44] Bullard, R. D. & B. Wright. *The Wrong Complexion for Protection: How the Government Response to Disaster Endangers African American Communities.* New York: NYU Press, 2012.
[45] Taylor, D.E. *Toxic Communities: Environmental Racism, Industrial Pollution, and Residential Mobility*. New York: NYU Press, 2014.
[46] Clark, L., Millet, D., Marshal, J. "National Patterns in Environmental Injustice and Inequality: Outdoor NO2 Air Pollution in the United States" *PLoS One, 9(4),* 2014. *https://doi.org/10.1371/journal.pone.0094431.*
[47] See, for example: National Academies of Sciences, Engineering, and Medicine. 2017. Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24651.
[48] See, for example, Ferdinand, Malcolm, "Decolonial Ecology: Thinking from the Caribbean World," Polity Press, 2022.

reminds us, “The colonizers and conquerors of the world…have never been confused about the scale of their ambitions for injustice.”[49]

How, you might wonder, does the artful sonification of data fit into this orientation toward repair? When composing with data, my relationship to the site of data collection and to the story within the data, all come together in the composition process. This makes the outcome undeniably subjective – something I write more about in the interlude. Furthermore, the compositions are not for another purpose. They are not to engineer efficiency, to support a policy decision, or to turn a profit. In artful data sonification, data becomes a conduit for connection to, and respect for, the place from which it came. For some datasets, the place from which the data came is the whole Earth.[50]

Art is not straightforward. It does not have a single or simple meaning or interpretation, it does not pretend to be objective, and this makes it particularly suitable for telling stories of climate change that resists viewing data as simply a utility for further advantage. Art paired with data can create a spaciousness around the data that leaves room for viewers/listeners' to slow down and sift through myriad layers of meaning, including the listeners' own relationship to the data.

My early works (chapter four) are primarily focused on drawing attention to the environmental crisis. Later works become more specific: in *Arctic Sea Ice* (chapter five) both human gesture – a pianist arms and hands – and pitch mournfully construe the satellite record of sea ice loss. The pieces in *Breathing in a Time of Disaster* (chapter six) weave together environmental data with recordings of human breath, resisting separation between the environment and the human body. The *Timescales Collection* (chapter seven) was written to create an experience in opening our senses to the long timescales of change that are evident in geophysical data. Through these works, I invite the audience to listen to a particular relationship with the data, one that intends to imbue a sense of respect, curiosity, sadness, alarm, or wonder for the air, ice, or lands from which the data came.

[49] Táíwò, Olúfẹ́mi, “Reconsidering Reparations,” Oxford University Press, 2021.
[50] I do not mean to conflate the act of listening to, or reconnecting to place through data, with the important material goals of reparations or decolonization. For more on this point see Tuck, Eve and K. Wayne Yang “Decolonization is not a Metaphor” in *Decolonization: Indigeneity, Education, and Society, Vol. 1, No. 1, 2012, pp1 - 40.*

Chapter 3. Data Sonification

> "I've never met an ecologist who came to the field for love of data or for the wonder of a p-value. These are just the ways we have of crossing the species boundary, of slipping off our human skin and wearing fins or feathers or foliage, trying to know others as fully as we can. Science can be a way of forming intimacy and respect with other species…"[51]

This chapter is an introduction to environmental data sonification. Data sonification, a form of auditory display, is the auditory analog to data visualization. While data visualization maps data to lines, colors, shapes, maps, etc., data sonification maps data to audio parameters such as pitch/frequency, amplitude/volume, rhythm, or timbre. While sonification takes many forms, not all of which are artful, my approach to sonification is in the spirit of science which Kimmerer articulates above; it's a way of honoring the lands, air, and waters of this planet. This chapter starts with a discussion of the benefits of the artful sonification of climate and environmental data. Then, I describe basic techniques and approaches to data sonification and propose a conceptual framework. Finally, I provide a snapshot of recent environmentally-focused sonifications by a variety of sound artists, composers, and scientists, showing the multiplicity of approaches to this evolving practice.

Why sonify climate data?

Not all environmental problems have proven as intractable as climate change. North American soils, once depleted of nutrients from high levels of acid rain, are beginning to show signs of recovery due to the emission cuts mandated by the U.S. Clean Air Act. [52] Critically endangered

[51] Kimmerer, Robin Wall, *Braiding Sweetgrass.* Milkweed Editions, 2013, pg. 252.
[52] Lawrence, Gregory, et. al., "Declining Acidic Deposition Begins Reversal of Forest-Soil Acidification in the Northeastern U.S. and Eastern Canada", Envion. Sci. Technol., (2015), 49, 22, 13102-13111. https://doi.org/10.1021/acs.est.5b02904

species have shown some recovery under protections from the U.S. Endangered Species Act, [53] and the Montreal Protocol's ban on ozone-destroying CFCs averted an imminent environmental disaster in the stratospheric ozone layer. One reason climate change has remained so difficult to address is that there is no simple or single policy solution, and it cannot be addressed by a single governing entity. All sectors of society contribute to the climate crisis – economics, agriculture, building design and materials, transportation, systems of defense, etc., although not all equally by all communities or nations. Redesigning all these sectors to protect the biosphere is a task of the imagination. As sociologist Kari Norgaard states: "If the broader public cannot imagine the reality of what is going on or imagine the level of change that is needed to change our course, then no forward movement will occur."[54] Data-inspired art is one way of sparking the imagination by upsetting common patterns of information-driven data consumption and creating new neural pathways through novel ways of experiencing data.

For decades, science communication relied on an information-deficit model of communication. In its most simple form, it posits that humans are rational actors who, if adequately informed of a problem, will seek reasonable solutions. And yet, decades of scientific reports about the imminent dangers of global warming have not led to actions commensurate with the crisis. There are many reasons for this, including entrenched interests in fossil fuel economics, the mismatch between the timescales of political decision-making and of climate change, and the energy needs of the global south to lift populations out of poverty. Another reason is psychological. When people are confronted with difficult information – a problem with no clear solution – cognitive dissonance and psychological distress can arise. The information deficit model of communication is ill-equipped to address psychological distress, and without emotionally intelligent means of processing difficult information, people tend to turn away from the problem defined by the information.

Climate-related psychological distress can manifest as depression or post-traumatic stress for survivors of disasters, as ecological grief, or as apathy or denial of climate change. Kari

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[53] Taylor, Martin, et. al., "The Effectiveness of the Endangered Species Act: A Quantitative Analysis." BioScience, Vol. 55, No. 4, 2005.
[54] Norgaard, Kari, *Salmon and Acorn Feed Our People,* Rutgers University Press, 2019, pg 239.

Norgaard is a sociologist who studied perceptions of climate change in 'Bygdaby', the fictional name of an actual rural community in Norway with a strong connection to nature and outdoor recreation. There, she found a form of denial of climate change that wasn't outright dismissiveness, but rather an inability to talk about it. She described hitting a conversational 'dead zone' when raising the topic of climate change. She writes that "the most effective way to manage unpleasant emotions is to turn one's attention to something else."[55] In this way, apathy toward climate change acts as a mask for suffering. More recently, Sarah Jaquette Ray has written a field guide on climate anxiety, specifically for young people like the environmental studies students she teaches. Reflecting on experiences with students in extreme states of distress after studying multiple overlapping environmental crisis, she writes that when students don't have the tools or proper support to process difficult emotions that rise, they can fall into what she calls "eco-nihilism – the notion that we should just erase ourselves because we are so bad for the planet."[56] Another related form of distress is the direct experience of environmental degradation, a form of grief which the environmental philosopher Glen Albrecht termed *solastalgia.* He introduced this word to name "the pain or distress caused by the ongoing loss of solace and sense of desolation connected to the present state of one's home and territory. It is the existential and lived experience of negative environmental change."[57]

Expressive arts are well known practices for working with grief and processing loss so that it does not become debilitating.[58] A collective experience of listening to a sonification of sea ice, composed with melancholy, can feel therapeutic – a reminder that one is not alone in their profound reaction to the evidence of our melting polar ice caps. Sonification can be a way of honoring or connecting with the places from which the data was collected; an expression of care and respect. The capacity for sound to convey a wide range of emotional tones makes it particularly well-suited for expressive representation of data.

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[55] Norgaard, Kari. *Living in Denial: Climate Change, Emotions, and Everyday Life.* MIT Press, 2011, pg 128.
[56] Ray, Sarah Jaquette, *A Field Guide to Climate Anxiety: How to Keep Your Cool on a Warming Planet*, University of California Press, 2020.
[57] Albrecht, Glenn. "Earth Emotions: New Words for a New World." Cornell University Press, 2019, pg 39.
[58] See, for example, Thompson, Barbara and Robert Neimeyer, Eds, *Grief and the Expressive Arts: Practices for Creating Meaning.* Routledge, 2014.

Furthermore, memorability is closely linked to emotional experience. Neuroscience and psychology studies show that emotional experiences leave much longer impressions in our brains, and memory of sounds and musical events is created through the auditory cortex rather than the visual cortex, so both the auditory and affective qualities of data sonification contribute to its memory imprint, which is neurologically distinct from visual memories.[59] Memorability, especially in relation to climate data, is important because people base judgements on information that is readily available in their memory. If evidence for climate change or impacts is difficult to retrieve from memory, its risks can be underestimated.[60]

A fundamental distinction between sonic and visual representations of data is the passage of time required to hear the sonic representation of data. Given the temporal quality of sound and the presence of temporal cycles in the earth system, rhythm can and is often a prominent feature of data sonifications. Whether it's simply marking a steady passing of time through the beat, representing daily cycles of sunlight and temperature, lunar-induced tidal cycles, or the many thousand year cycles of ice ages driven by orbital forcing, auditory data representations can create experiences in which listeners feel the temporal cycles in the earth system. Unlike a graph, a sound composition cannot be perceived in a single instant; the listener must experience the sounds as they unfold. If the sonification is of data that was collected over time (i.e., time series data), then the sonification translates, or maps, historical time to musical listening time. This can bring explicit recognition to the passing of time and to the relationship between the duration of the sonification and the time scales represented in the data, allowing listeners to actively shape their temporal perspectives of climate change.

In addition to the temporal duration, the experiential aspect of sound and music allows for different use of the physical space in which the data is heard. Headphones aside, sound reverberates through the physical space, and allows listeners or audiences to move around and/or shift their posture or gaze without interrupting the connection to the sound. This can be helpful for kinesthetic learners, and can reduce visual fatigue that is common in classroom and formal presentation settings. Even though auditory processing occurs in the brain, listeners have

[59] I've learned about the durability of musical memory, which shaped my interest in sonification, from personal experience. This is described further in the interlude.
[60] Pahl, Sabine, et. al., "Perceptions of time in relation to climate change." WIREs Climate Change, 2014.

described feeling sonifications with their whole bodies.[61] In chapter six I describe a set of compositions that use the directionality of sound as part of the sonification that represents geographic disparities in air quality.

Although data sonification is primarily an auditory process, it also often includes visual elements. In performance, these visual elements can increase understanding of how the sound represents the data. The sonification of Beijing's air quality data by Brian Foo, which I will describe more fully later in this chapter, is presented as a video with a movie of the data playing in sync with the song. The Climate Music Project is a performing arts organization that does multimedia performances with musicians on stage and a visual display in the background. Sonifications for human performance, such as the *Arctic Sea Ice* composition for piano, or the *Song of Our Warming Planet* for String Quartet, include bodily gesture and movement as part of interpretation of the data. Each musician in the string quartet represents a different latitude band in Song for a Warming Planet. In the *Arctic Sea Ice* composition, the left and right hands each have distinct meanings, and the position of the hands tells the audience whether the sea ice cover is above or below normal levels. The physicality of these performances creates multisensory connections between data, performers, and listeners.

In the next section, I briefly outline a theory of sonification, then describe examples from different sound artists. For a comprehensive review of sonification techniques for practitioners, see *The Sonification Handbook*.[62]

A Brief Introduction to Sonification

Quantitative data are numerical records of measurable properties or relationships. To identify patterns or meaning in the numbers, scientists have developed elaborate ways of representing data visually. But the eyes are not the only sense organs capable of interpreting data. Data sonification, a subset of auditory display, uses non-speech audio to represent information.[63]

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[61] See listener feedback in chapter seven.
[62] Hermann, Thomas, Andy Hunt, and John Neuhoff, editors. *The Sonification Handbook*, Logos Publishing House, 2011, available at: https://sonification.de/handbook/
[63] Walker, Bruce N, and Machael Nees, "Theory of Sonification," in *The Sonification Handbook* (ibid).

Sounds are pressure waves that cause vibrations in the ear drum. The frequency of pressure waves is perceived as pitch, which is the sensation by which sounds can be ordered on a musical scale.[64] The average human ear's ability to hear differences in pitch is quite sensitive. It varies somewhat as a function of the pitch, but the range is between 1 Hz (Hertz is a unit of frequency – cycles per second) for low pitched sounds around 100 Hz, and up to 3 Hz for sounds around 1 kHz. And while two instruments can play the same pitch, the quality of sound, called timbre, can vary immensely. This is due to the complexity of different waveforms within the sound. The typical range of audible pitch is 20 - 20,000 Hz, though this varies among individuals and across one's lifespan. The perceived volume of sound is a function of both the intensity and frequency of the pressure wave. These basic features of the physics and psychophysics of sound allow for a wide variety of approaches to data sonification.

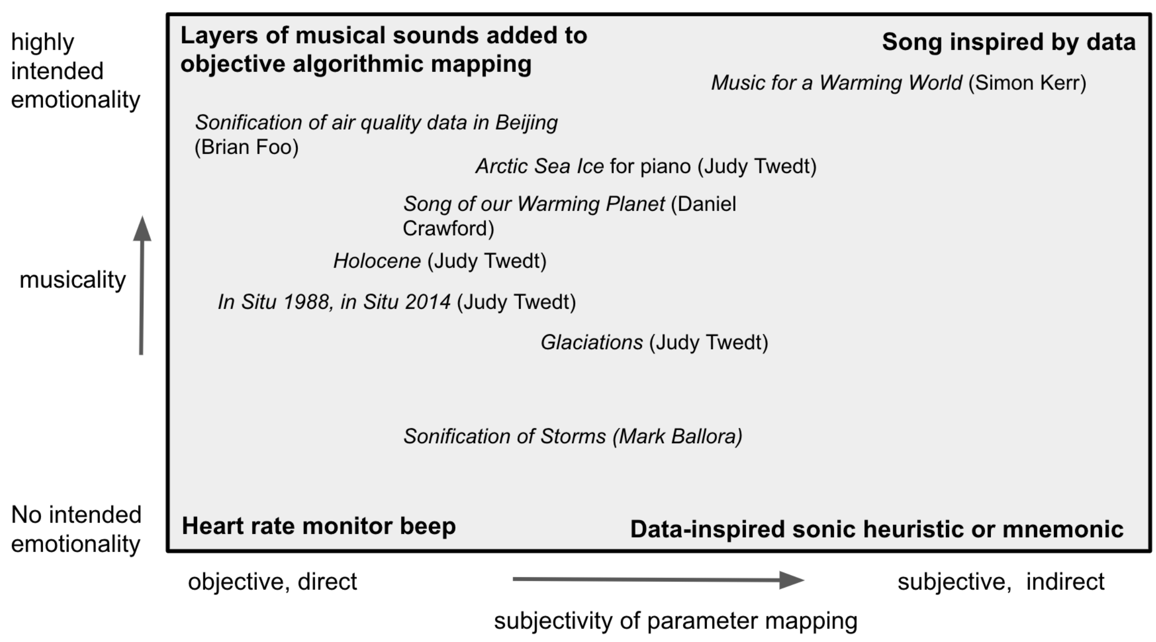

Figure 3.1 Sonification scheme

Sonification can be made through a wide spectrum of auditory displays. The most direct sonic displays of data are often referred to as 'audification.' Common examples of audification are

[64] Carlile, Simon. "Psychoacoustics, " in *The Sonification Handbook* (ibid).

translating measurements from a heart rate monitor to audible beeps, or translating a measured waveform (like data from a seismograph or a telescope) into an audible frequency. On the other end of the spectrum, musical sonifications interpret data with artful human expression, and often through complex mappings.

To understand the spectrum of approaches to sonification, I offer a two-dimensional design framework, shown in figure 3.1. One dimension, shown across the x-axis, is the subjectivity of parameter mapping. This ranges from objectivity, with very direct mapping of data to sound, to highly subjective mapping of data which could include the use of musical scales or metaphorical sounds. Another dimension, shown across the y-axis, is the intended musicality. A highly objective parameter mapping is a common heart rate monitor, which maps the heart rate to a single frequency that we recognize as a beep. This direct mapping uses little to no subjectivity, only the choice of beep frequency and duration. Similarly, the Keeling Curve of atmospheric carbon dioxide may be mapped to a chosen frequency range which we hear as pitch. In this case the choice of frequency range is analogous to the limits of the y-axis in a visualization. And similarly, the choice of line thickness, style, and color in visualization is analogous to the choice of sound quality (i.e. the 'beep' could be sonified with a sine wave, square wave, sawtooth, etc…). These examples – the heart rate monitor and the direct mapping of the Keeling Curve to frequency (pitch) – use little subjective choice in parameter mapping. Examples of more subjective parameter mappings include using a musical scale or the sound of a musical instrument or timbre, in which each note has a range of harmonic frequencies that give it a particular sound quality. Or, in the case of highly subjective parameter mapping – a less direct algorithmic approach is used and the sound is an interpretive representation of the data.

Both personal preference and culture determine the perception of musicality, but this y-axis dimension provides a framework for discussing choices made in compositional approach. There is no musical intent in a heart rate monitor. Similarly, some sonifications of environmental data, particularly those for exploratory data analysis, have no intended musicality. Their purpose is primarily to inform, not to stir listeners emotions. Auditory displays with higher levels of musicality are more likely to create lasting impressions or memorable experiences. Brian Foo's sonification of air quality data in Beijing includes both a direct, algorithmic parameter mapping of particulate matter and uses rhythm and industrial music to create associations to the data. Layers of sound added to the data sonification, including environmental sounds of car honking in a busy street, connect the data to its environment in the mind of the listener.

Current Practices and Practitioners of Climate Sonification and Climate Music

A growing number of scientists, composers, digital sound artists and science communicators use sonification and music to represent environmental data. Here I describe a sampling of approaches, from objective data sonification to data-inspired music:

The original SimEarth video game, published in 1990 by Maxis, included a datasound menu that sonified data for aural monitoring while playing the game. For example if the player wanted to combat global warming, they could set their tone monitor to listen for air temperature. Other datasets for sonification in the game include altitude, rainfall, sea temperature, and biomass.[65]

In New York, Brian Foo, an artist and computer programmer also known as Data-driven DJ created a series of music experiments that combine data, algorithms, and recorded sounds. Presented as a music video, his *Sonification of air quality in Beijing*[66] uses daily PM 2.5 readings and is entirely algorithmic. The sounds used come from samples of a single track of industrial music, *32 Ghosts,* from Nine inch Nails, and the design style uses clusters or masses of sound samples to represent daily PM2.5 readings from 2012-2014. The data maps to sound clusters that distort or 'pollute' the sample sound when PM2.5 levels are high. The listener both sees and hears this time series in just under five minutes.

In the visitors center at the National Center for Atmospheric Research in Boulder, Colorado climate scientist Clara Deser and sonification artist Marty Quinn created an interactive sonic

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[65] Original SimEarth user manual, accessed 5/22/23 at https://www.lemonamiga.com/games/docs.php?id=1454

[66] Foo, Brian, *Airplay: Smog Music Created with Beijing Air Quality Data*, in the collection Data Driven DJ: https://datadrivendj.com/tracks/smog/, accessed 5/6/2023.

installation to explore and hear scenarios from climate models.[67] This installation uses a touch-screen graphical display with which the user explores data from 40 model runs of the Community Earth System Model Large Ensemble Project. Mapping the parameters temperature, precipitation, carbon dioxide, and sea ice to pitch, with different instrumental sounds for each parameter, the user can listen to historical and future projections of climate parameters anywhere in the world. By sonifying the model ensemble data, the installation helps the user understand concepts such as signal-to-noise ratio and model variability.

Bridging the microscopic and macroscopic, Tim Weaver's *cytoDoptera*[68] is a sonic work composed from respiratory/electron transport proteins of the endangered Monarch Butterfly. The composition layers sonification, ambient sound recordings, and samples of percussion performance in a "sonic investigation into the multi-scale interactions of the North American Monarch Butterfly flight path." Mixing sonification of biological data together with recordings of the monarch butterfly's avian predator, the Black Headed Grosbeak, and percussive sounds made of rattles from the cocoons of butterflies and moths, the piece invites the listener to consider the relationship between predation, climate change, and the microbiology of this charismatic North American Species.

Seismic Sound Lab,[69] at Lamont Doherty Earth Observatory, uses sonification to convert seismic data into audible frequencies. Mixed with video animation and often performed in the planetarium at the American Museum of Natural History, listeners hear and see how the global network of seismometers reveals the complex patterns of earthquakes moving through time and space. The Sound Lab has produced works on themes ranging from human induced seismicity from well injection in Oklahoma to wave propagation, convection and tectonic plate motion.

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[67] Gardiner, L.S., et. al., "Sounding Climate: An Exhibit Showcasing Data Sonification and Visualization from the Community Earth System Model." American Geophysical Union, Fall Meeting 2018, abstract #PA41B-03. Video tutorial accessed 4/30/2023 at: https://scied.ucar.edu/exhibits/sounding-climate.

[68] Weaver, Timothy, *cytoDoptera* (2008). Accessed 4/30/2023 at: http://tweaver.biotica.org/cytodoptera.html

[69] http://www.seismicsoundlab.org/, accessed 5/6/2023.

An artist and Associate Professor of Art and Ecology at the University of New Mexico, Andrea Polli, began collaborating with atmospheric scientists on sound and sonification projects in 1999. *Atmospherics/Weather Works*[70] was a spatialized sound installation using model output of historic storms in the continental US at elevations ranging from sea level to the top of the atmosphere. *Sonic Antarctica*[71] is a radio broadcast, live performance, and sound installation that blends natural field recordings, interviews with scientists, and sonifications of climate data to bring the listener into connection with the place, the people, and the scientific process at McMurdo research station and the South Pole. *Heat and the Heartbeat of a City*[72] is a set of sonifications that allows listeners to move through time and experience the effect of consecutive days over 90 degrees Fahrenheit. Using noises designed to be somewhat uncomfortable, Polli designed the sonification with the intent to make people feel the impacts of global warming and think more seriously about the issue.

In the wake of devastating hurricane seasons, meteorologist Jenni Evans and music technologist Mark Ballora collaborated to sonify the dynamics of tropical storms,[73] to help people better understand how extreme storms evolve. Their single-storm sonification maps four parameters: air pressure, latitude, longitude, and asymmetry to acoustic parameters that sound stormy. They've also created an audiovisual mapping of global storm activity from 2005,[74] to see and hear the temporal and spatial evolution of storms, their intensity, and their seasonality. Ballora's approach to this sonification of meteorological data is informative but not intended to be emotionally evocative, and shows how the technique can be used as a close analogue to a visual graph.

[70] Polli, Andrea, "Atmospherics/Weather Works: A Spatialized Meteorological Data Sonification Project." Leonardo, Vol 38, No. 1 (2005), 31-36.
[71] Polli, Andrea, "Sonic Antarctica," Gruenrekorder, 2009.
[72] Polli, Andrea. "Heat and the Heartbeat of the City: Sonifying Data Describing Climate Change." *Leonardo Music Journal*, vol. 16, 2006, p. 44-45. *Project MUSE* muse.jhu.edu/article/207768.
[73] Evans, Jenni and Mark Ballora, "Turning hurricanes into music: can listening to storms help us understand them better?" The Conversation, December 4, 2017. Accessed 4/30/2023 at: https://theconversation.com/turning-hurricanes-into-music-can-listening-to-storms-help-us-understand-them-better-88203
[74] Ballora, Mark, "Sonification of Storms Year 2005," 2017. Accessed 5/1/23 at: https://youtu.be/TKTLE1rRUDA

John Luther Adams, a composer whose music is inspired by landscapes, wildlife, and ecology, has also worked with data sonification. Naalagiagvik, *The Place Where You Go to Listen*, is a sonic installation and permanent exhibit at the University of Alaska Museum of the North. The installation of light and sound features real time sonification of seismic and electromagnetic data to create a virtual listening experience that resonates sympathetically with the real world. The composition sonifies seasons, the time of day, changes in the phases of the moon, and weather conditions, and seismic data from Alaska.

Sonifications can also take the form of live performance: Cellist Daniel Crawford composed *Song of our Warming Planet* from global temperature data, and two years later, collaborated with Scott St. George to map surface temperature data from multiple latitude bands to the instruments in a string quartet in *Planetary Bands, Warming World.*[75] With temperature mapped to pitch, each instrument represents a different latitude band; the violin sonifies Arctic warming and uses nearly its entire instrumental range.

The Climate Music Project brings together scientists, composers, visual artists and performers performances that combine data sonification and highly interpretive musical representations of data together with video. Their performances span the range of algorithmic composition interpretive sound, and have created a range of collaborations between scientists, composers and performers. For example, *Climate Momentum* is a piece about the lag times between emissions and climate impacts using modeled projections of sea level rise. Created in a collaboration between scientists from Lawrence Berkeley National Lab and the San Francisco Conservatory of Music, the piece combines live performance of data-driven electronic music with audio visualizations.

On the interpretive spectrum of climate and environmental music, artists such as Simon Kerr and internationally renowned indigenous experimental vocalist Tanya Tagaq, integrate science of the environment into their music and art. Noting that music has an evolutionary function in supporting social solidarity, Simon Kerr writes and performs climate music to raise climate

[75] St. George, Scott, et. al., "Making Climate Data Sing: Using Music-like sonifications to Convey a Key Climate Record," Bulletin of the American Meteorological Society, Vol 98, Issue 1, 2017. DOI: https://doi.org/10.1175/BAMS-D-15-00223.1

consciousness which, "means not just that one is vaguely aware of the climate challenge, seen dimly, but that this awareness is deeply alive in our consciousness, we have a heightened awareness."[76] Kerr's *Music for a Warming World*[77] is a four part musical performance combining storytelling with song and imagery. Using a narrative structure and a combination of music, videos, and still images, they take the audience through the physics of climate change to the experience of loss, actions for mitigation, and to a reflection on the impermanence of life.

Tanya Tagaq, an Inuit throat singer and experimental vocalist whose work is intimately connected to the arctic landscape and ecological degradation, channels sounds and changes from her environment into rhythmic tapestries through vocal, instrumental, and electronic elements. The lyrics of her song *Cold* describe the release of latent heat of water: "If you take a gram of water // and apply one calorie of heat to it // you will raise its temperature by one degree Celsius // but you need to apply 81 calories // to ice, simply to change it to water at 0 degree Celsius…"

This spectrum of works outlined here represents the range of uses for auditory display in climate science communication, from direct and low-affect sonification to highly interpretive music and song. Scientists, artists and musicians are using multiple formats from digital sound files to installations and live performance. In all cases, sound creates a visceral connection to the data which listeners experience over time.

Conclusions

Overhead projectors, transparencies, newspapers and magazines required scientific information to be communicated exclusively through text and visual media but these print media are no longer the dominant modes of publication and presentation. Nearly all formats in which science is presented today – online publications, seminars, radio and podcast, classrooms and conferences – include audio and video technology.

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[76] Kerr, Simon and Christine Parker, "Making Climate Real: Climate Consciousness, Culture, and Music," King's Law Journal, 2019, Vol. 30, No. 2, 185-193. doi.org/10.1080/09615768.2019.1645428
[77] https://www.musicforawarmingworld.org/, accessed 5/6/2023.

And the expanding capability for auditory media coincides with the growing recognition of the need to shift to new models of science communication. Decades of research in psychology, cognitive science, and sociology has identified the limitations and inefficacies of the information-deficit model of communication, with its overreliance on the objective delivery of abstract information.[78,79,80,81] Statistical information, by itself, has very little influence on decision-making and risk assessment. Information is meaningful to others when it is embedded in a social and cultural context that helps people construct feelings about the information.[82] This is especially important amidst the rise in damages and loss from climate change and the associated feelings of grief and climate anxiety.[83]

When data and scientific information is expressed as sound or music, it is a dynamic event in time. Without using color, light or text, it can express the rise or fall of temperature, sea ice, wind speed. Natural diurnal and seasonal cycles can be felt viscerally, and temporal changes can be experienced by the listener. This use of sound and music to communicate climate science is driving interdisciplinary collaborations between artists, scientists, composers, and performers, and creating more contexts by which public audiences engage with climate science which creates more transferable knowledge.[84] In the following chapters, I will present sonifications that express climate data sets of global mean surface temperature, atmospheric carbon dioxide, arctic sea ice extent, and air pollution.

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[78] Shi, Jing, et. al., “Knowledge as a driver of public perceptions about climate change reassessed,” Nature Climate Change Vol. 6, pg 759-762, 2016.
[79] Moser, Susanne, “Reflections on climate change communication research and practice in the second decade of the 21st century: what more is there to say?” WIREs Clim Change 2016, 7:345–369. doi: 10.1002/wcc.403
[80] Roeser, Sabine, “Risk Communication, Public Engagement, and Climate Change: A Role for Emotions,” Risk Analysis, Vol. 32, No. 6, 2012 DOI: 10.1111/j.1539-6924.2012.01812.x
[81] Sawe, Nik, et. al., “Using Data Sonification to Overcome Science Literacy, Numeracy, and Visualization Barriers in Science Communication,” Frontiers in Communication, 2020 Vol. 5:46, DOI: 10.1111/j.1539-6924.2012.01812.x
[82] Norgaard, 2011.
[83] Cunsolo, Ashlee, and Neville Ellis, “Ecological Grief as a mental health response to climate change-related loss,” Nature Climate Change, 2018, Vol. 8, 275-281, doi.org/10.1038/s41558-018-0092-2
[84] National Research Council, 2000. *How People Learn: Brain, Mind, Experience, and School: Expanded Edition.* Washington, DC: National Academies Press. https://doi.org/10.17226/9853.

Interlude: The People and Places that Influence this Work

This body of work is a product of skills and lessons I've learned over many years, and also of multigenerational influences. Here, I share a little about the people, experiences, and places outside of academia that directly or indirectly influenced this work.

I was born in Tacoma, Washington, a port town on Commencement Bay with sweeping views of Mount Rainier - a grand, glacier-covered peak that rises up out of the foothills of the Cascade Mountains. My parents are both music teachers. My mom taught music in public elementary schools and my dad taught private piano lessons at our house in a middle class, white neighborhood.

Music was the glue of my family. My parents met through my maternal grandpa, who taught piano at Pacific Lutheran University and was my dad's undergraduate advisor. Both of my mom's parents were pianists, and my mom's four other siblings played instruments, as well. In our family, music was both a profession and sacred activity; my dad and grandpa directed church music and choirs, and I sang and performed for countless services. Music was my favorite part of religious worship. From grade school through high school, I played piano and flute. It was something I enjoyed, though I never imagined doing anything with music professionally. When, in my early 20s, I became disillusioned with the paternalism and patriarchy of the church and left, it was the music traditions that I missed.

Family on my mom's side has lived on the lands of the Coast Salish people for six generations as settlers and homesteaders. My great-great grandpa was orphaned as a young boy in Pennsylvania. When he turned 16, he lied about his age so that he could enlist in the union army with his older brother. His brother died a year later in an army hospital, but my great-great grandpa survived and, after prospecting for gold in Nome, Alaska, bought land and homesteaded on what is now Carr Inlet in the southern basin of the Puget Sound. This was the land on which I lived in my early childhood, in a modest house on a small bay. Land ownership and the old growth trees that came with it created middle class wealth for my family, and although we loved hiking in the mountains and spending time together in nature, we rarely talked about our family's history of logging old growth trees.

My dad grew up on a farm in South Dakota on Oceti Sakowin land, a farm that my ancestors obtained through the Homestead Act when they settled here after immigrating from Norway; the name of the farming community is *Norway Township*. My dad went to a one-room schoolhouse, milked the family cow in the morning, and spent his summers, and time outside of school, helping with farm work. This farm created enough wealth to send my dad to college where he met my mom. As a kid, I had a vague understanding that many generations of my family had lived on that farmland; it was the American roots of our family.

I have two older siblings, both of whom have intense connections to animals and significant cognitive disabilities, and so my parents were often consumed with helping them navigate the school system. Experiences outside of the city – hiking, swimming, and playing near the beach – were the best part of my childhood. As an angst-ridden teenager of the late 90's, I found solace being in the mountains and the saltwater bays that shape western Washington. For college, I was determined to be near mountains, and went to Colorado College, a bike ride away from Pikes Peak and the Front Range. When teenage angst turned into a multi-year mental illness, it was summers working and living in the mountains of Washington, Colorado, Utah, and Montana that kept me steady enough to cope and eventually recover my mental health. Originally intending to study geology at Colorado College, I discovered philosophy and fell in love with the questions we studied in those courses, so I chose an interdisciplinary program in history and philosophy, and studied environmental ethics and human rights theory. I spent a summer doing independent research in environmental ethics and then left college for a year to work as a human rights observer with Fray Bartolomé de las Casas Centro de Derechos Humanos in a rural, autonomous Zapatista village in the forests of Chiapas.

After graduating and working as a teacher and tutor in Amman, Jordan and in Washington DC, I returned to my home in Tacoma to go back to school to eventually work in environmental sciences. I started at Tacoma Community College, and worked my way into a doctoral program in Atmospheric Sciences. While taking classes at my hometown community college, I also started visiting my grandparents regularly. My grandpa, retired from teaching, performing, and choral directing, had dementia and I found that we could connect through music. Although he could no longer remember a schedule, he was almost always available for drop-in piano lessons, and teaching piano brought him back to himself. He could teach, and play music, with almost no signs of memory loss. I say *almost* because he didn't have a strong sense of present time, so often our lessons would go up to two hours before I'd have to tell him that *I* needed to rest. These lessons with him taught me that music has a special place in human memory, and a capacity to enliven us even as disease takes hold of other parts of the body. These lessons were also my first experience with music as a medium for time travel. Piano music brought us back to a time before dementia seized many of my grandpa's cognitive processes.

Later, while working on my masters degree in Atmospheric Sciences, I was a member of my student employee labor union, UAW 4121. Through my union, I became involved in a climate caucus within the King County Labor Council – an organization representing all of the unions in King County – where I founded a speakers bureau on climate change. I organized students from different disciplines to give talks to labor unions throughout the County – postal workers, electrical workers, painters, teachers, etc... This work taught me how to see climate science through the lenses of people in many different trades. For example, delivery drivers shared their difficulties staying cool on hot days in delivery trucks that didn't have doors, and thus no air conditioning. Postal workers also faced health risks from extreme heat. I spoke with one outdoor worker whose knowledge of climate change came entirely from helping his 5th grade daughter with her science homework. During a particularly bad wildfire in the summer of 2017, Honest Ibarra, a 28-year old farmworker in northwestern Washington died. He had preexisting health conditions and was denied adequate time to hydrate and rest. He was a father of three children. In fury over his death, his fellow farmworkers went on strike to protest their working conditions. The farm management promptly fired them, but their temporary H-2A visas were tied to their employment so they were stuck in legal limbo with no housing because, under immigration law, the farm provided their housing. In my union, we organized some aid and a caravan of people to support their protests, and eventually the farmworkers were able to return home. These conversations and experiences shifted my interest away from basic climate research and towards science communication and environmental justice. It was around this time that I began experimenting with data sonification. The story of my early sonification experiments continues in chapter three.

For the next few years, I continued to organize union efforts in climate and environmental justice. Through coalition work between unions and environmental organizations, we passed climate legislation at the city and state level, all while I was taking classes in digital sound synthesis in the program in digital arts and experimental music (DXARTS), and also teaching undergraduate classes.

Just before COVID-19 brought the world to a slowdown, I moved to Vashon Island, a small rural island with my partner; it's a short ferry ride from Seattle. This was a lucky place to be during the long shutdown. Introverted by nature, I invigorated a meditation practice that I had started several years prior, and took many long walks. A small grove of giant Sequoia trees on a bluff above the water became one of my favorite haunts. I taught remote classes on climate writing, and in the summer of 2021 on the tail end of a big heat wave, I gave birth to a baby. The year following her birth, I stepped back from activism, teaching, and my sonification work and tended to this tiny human. I'd never felt such a direct, visceral connection to the future.

Both COVID and childbirth were experiences of time warp, where the rhythms and texture of time in daily life shifted, and the world changed. When I came back to finish this dissertation, Mattie was one year old and I felt I needed to compose the *Timescales of Carbon* collection, which I write about in chapter seven. This collection is a meditation on time, and an attempt to connect with progressively longer planetary time scales. The connections between these sonifications and environmental justice are not direct, and for some time I felt tension between these two threads of my work. One aims for an inward, personal understanding of climate change by listening to climate data; the other for an outward shift in the law and structures that shape our lives on this planet. It's my hope that, as this work continues to unfold in the world, these sonifications will weave together with work in environmental justice, albeit in ways that might not be obvious, creating a tapestry that supports the resilience of the biosphere in the decades to come.

Chapter 4. Digital Works (2016 - 2017)

The idea of converting climate data into sound came to me while I was finishing a masters degree in atmospheric sciences and teaching introductory undergraduate classes on global warming. I noticed that some students had very strong reactions to information about global warming, others appeared to have little interest. Either way, the data was something they might have to interpret on an exam, becoming, for many, a source of anxiety. This significantly limited their capacity for open ended and curiosity-driven connections to the data. Furthermore, all of the data sets were presented with similar data visualizations (line graphs, bar charts, color maps, etc…). I wanted a way to show and express some of the more significant data sets in ways that fostered emotional connection. As an amateur musician, I was comfortable working with musical notation, and it seemed possible to me that the data could be converted to pitch and listened to over some time period, allowing the listener to encounter the data as an experience, rather than as an object to view instantaneously. From personal experience living with siblings with disabilities, I was also keenly aware that multisensory instruction improves learning and engagement with new material. With these considerations in mind, I spent a weekend exploring ways to generate sound in Python, the programming language that I was already using for data analysis and visualization. This experiment led to the creation of a simple sound file that would ultimately become a music video about the Keeling Curve, titled *The Deafening Rise of Carbon Pollution*.

In this chapter I outline the data and composition process behind three early works, by which I mean works that were composed prior to any formal training in digital sound composition. They were made with simple sound libraries in Python, and they generated such strong interest among teachers, reporters, bloggers, and students, that I decided to continue to pursue the experiment as my primary line of creative scholarship.

Data

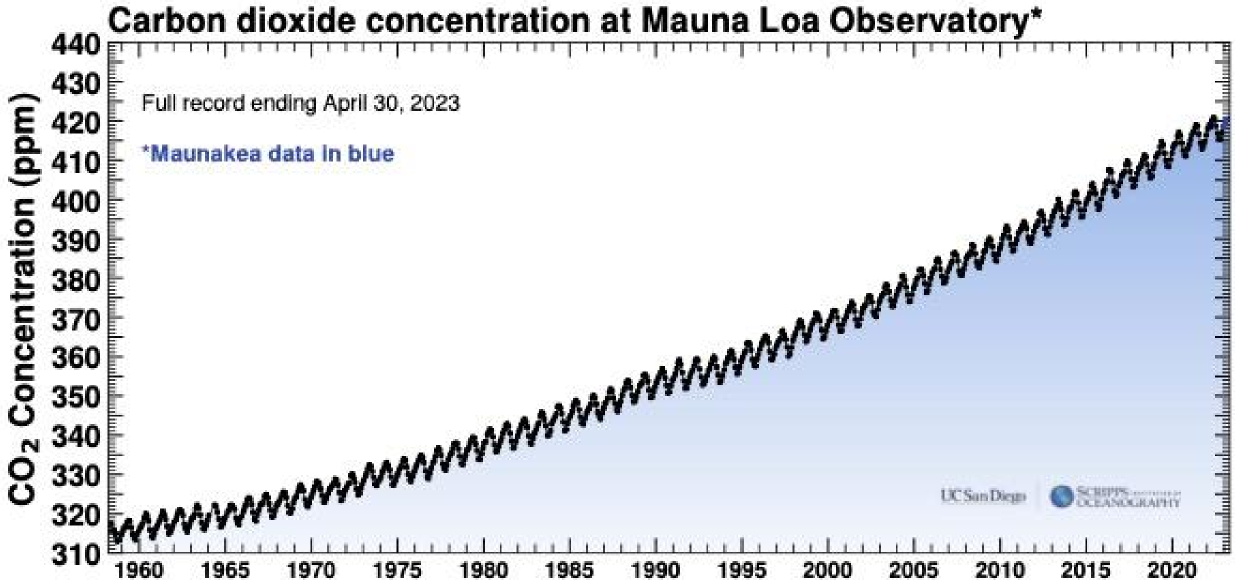

Figure 4.1 Monthly record of atmospheric carbon dioxide. Image from Scripps Institution of Oceanography at UC San Diego.

The longest continuous measurement of global carbon dioxide was started and originally maintained by Charles Keeling at the Mauna Loa Observatory in Hawaii (figure 4.2).[85] The story of this dataset is a personal story of a scientist driven by curiosity and fortunate enough to secure institutional support across different federal administrations. As a 27 year-old postdoctoral fellow at CalTech looking for a research project, Keeling described, in his memoir, designing a field experiment to test an idea about the amount of carbonate in surface water. This required knowing the atmospheric concentration of CO_2. At the time, estimates of background concentrations of CO_2 varied widely in the scientific literature, and so Keeling began making his own direct measurements. Rooftop samples from the geology building, he found, varied widely owing to the local emissions from cars, industry and backyard incinerators, and so he began taking measurements a full day's drive away in the pristine air next to the Pacific Ocean at Big Sur. His sampling strategy was more elaborate than required by the experiment, but "I was

[85] C. D. Keeling,et. al., "Exchanges of atmospheric CO_2 and $13CO_2$ with the terrestrial biosphere and oceans from 1978 to 2000." I. Global aspects, SIO Reference Series, No. 01-06, Scripps Institution of Oceanography, San Diego, 88 pages, 2001. http://escholarship.org/uc/item/09v319r9

having fun. I liked designing and assembling equipment. I didn't feel any pressure to produce a final result in a short time." Eager to learn more about the daily cycle that he observed in the measurements, he focused his attention on atmospheric CO_2 monitoring, and began recording observations "everywhere I went, from the rainforests of the Olympic Peninsula near Canada to the high mountain forests of Arizona near Mexico," and he found that afternoon air concentrations were nearly constant everywhere he went: 310 parts per million. This result ran contrary to scientific literature, and his observations grew large enough that he brought them to the attention of the director of Meteorological Research at the US Weather Bureau in 1956. Two years later, a systematic monitoring of atmospheric CO_2 at the Mauna Loa Observatory began.[86] Now a canonical climate dataset, the Keeling Curve is presented to students around the world as the evidence of rising atmospheric carbon dioxide. So basic to understanding climate change, this was the first dataset that I sonified.

Composition process

I used monthly average values to sonify two layers of story within the data: the first is the seasonal cycle, which can be heard going up after vegetation recedes in the fall and winter, and going down after vegetation grows in the spring and summer. In the background of this strong seasonal cycle is a yearly rise in CO_2 due to human emissions. These two stories create rhythm (the seasonal cycle) and direction (the long-term rise), which I suspected would be very interesting to listen to.

The final product – a music video that layers text and images with the sonification – was a collaborative effort between me and Dargan Frierson, my graduate advisor and a climate scientist and musician who had a reputation for writing and performing his own climate music in his classes. I began by experimenting with a Python music library called PyKnon, a 'simple python library to generate music in a hacker friendly way."[87] I translated the CO_2 values to a chromatic scale using midi notes, settled on a tempo that had an energetic pace, set a pitch range

[86] Keeling, Charles. "Rewards and Penalties of Monitoring the Earth." Annual Review of Energy and the Environment, 1998. 23: 25 - 82. Accessed 5/6/2023 at: https://scrippsco2.ucsd.edu/assets/publications/keeling_autobiography.pdf

[87] Kroger, Pedro. Pyknon Github repository: https://github.com/kroger/pyknon, accessed 5/6/2023.

that was unpleasantly screechy at the end of the record, and shared it with Frierson. He added a drum beat and set it in a music video with subscripts that explained how the data was mapped to sound.

As an experiment in drawing more public attention to climate data, the result exceeded my expectations. A local reporter picked it up and it eventually aired on National Public Radio, PBS NewsHour,[88] EarthSky[89] and was also featured in print media and on podcasts. The video was translated into Portuguese and included in a museum exhibition called "Climate Change and the Oceans of Tomorrow" and on tour to schools throughout Portugal.[90] The amount of interest that this sonification generated ultimately motivated me to design an interdisciplinary PhD program so that I could focus exclusively on rendering climate data through music.

The Sound of Earth's Fever

Data

On June 23, 1988 Dr. James Hansen, the director of NASA's Goddard Institute for Space Studies, testified before the senate committee on energy and natural resources stating that global warming could be observed in Earth's surface temperature records: "the greenhouse effect has been detected, and it is changing our climate now."[91] Hansen had created a scheme for estimating global temperature change in the late 1970's to compare with predictions from simple climate

[88] Ryan, John, "Listen to 58 years of climate change in one minute", PBS News Hours October 31, 2016, accessed at: https://www.pbs.org/newshour/science/listen-58-years-climate-change-one-minute
[89] Byrd, Deborah, "The Sound of Climate Change." EarthySky, October 17, 2016. Accessed at; https://earthsky.org/earth/keeling-curve-atmospheric-co2-set-to-music/
[90] Exhibition, curated by Marta Pimento, was displayed at the Museum Museu do Mar Rei D Carlos I in Cascais, Portugal from February 13 - July 31, 2019. See appendix v for more information about this exhibition.
[91] Hansen, James. "Greenhouse Effect and Global Climate Change" Testimony before the Committee on Energy and Natural Resources, United States Senate, June 23, 1988. Accessed at: https://pulitzercenter.org/sites/default/files/june_23_1988_senate_hearing_1.pdf

models, and the dataset he started,[92] updated by a series of improvements over time, was the focus of our second music video.

The dataset is called GISS Surface Temperature Analysis (GISTEMP, figure 4.2). It is an average of both land and sea surface temperature anomalies. The anomalies show how different the temperature is relative to a 30-year average (from 1951 - 1980). The land temperatures are from NOAA's meteorological stations known as the Global Historical Climatology Network (GHCN). Sea surface temperatures are derived from the International Comprehensive Ocean-Atmosphere Datasets (ICOADS) which uses both satellite data and ocean based measurements. In this sonification, we used annual average global mean surface temperature starting in 1880 and ending in 2016. At the time of composition, 2016 was the warmest year on record.

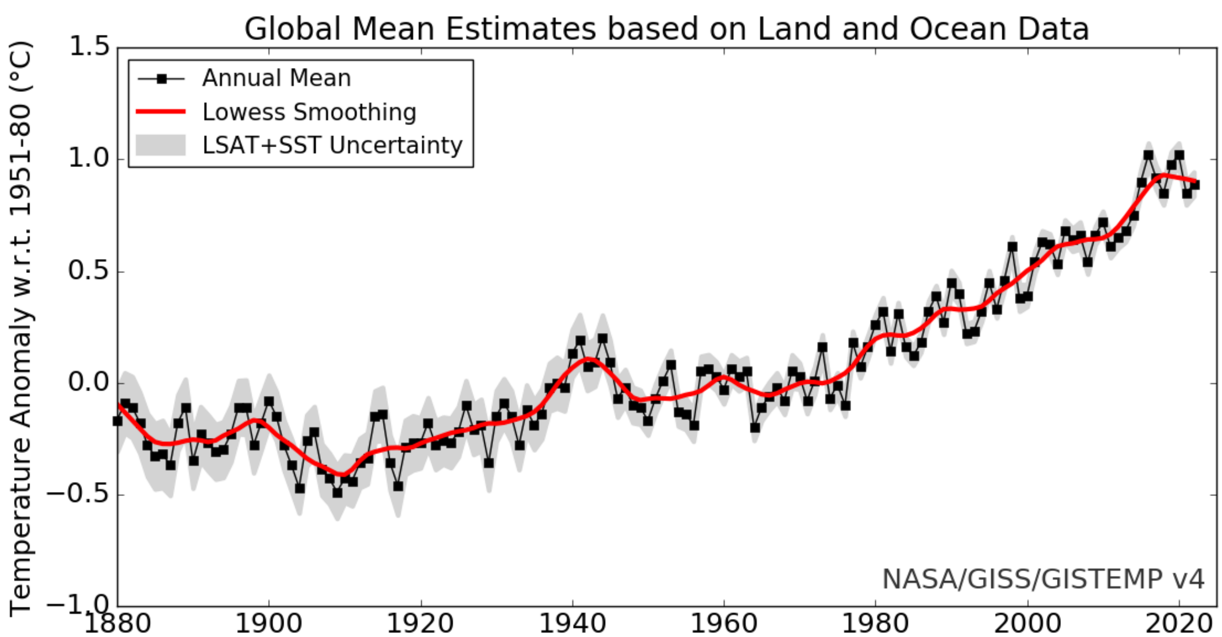

Figure 4.2 Land-ocean temperature index, 1880 to present, with base period 1951-1980. The solid black line is the global annual mean and the solid red line is the five-year lowess smooth.

[92] GISTEMP Team, 2023: GISS Surface Temperature Analysis (GISTEMP), version 4. NASA Goddard Institute for Space Studies. Dataset accessed at https://data.giss.nasa.gov/gistemp/.

Composition Process

This piece was also a collaboration with Dargan Frierson. Similarly to the sonification of the Keeling Curve, I mapped the GISSTEMP data to midi pitch values using PyKnon, this time to a six-octave whole-tone scale. Each annual average anomaly datapoint is one note, and because there is no missing data and no seasonal cycle, this composition does not have any inherent rhythm or patterns, other than the long-term rise. After mapping the data to midi notes, we imported it into Garageband and layered electronic beats to the data. Additionally, we paused the sonification in the year 1977 and added a voiceover announcing the temperature rise. In the music video, the images and text explain that this was the year in which oil company ExxonMobil's senior scientist James Black presented research that fossil fuel burning caused global warming.[93] This video was featured in a news story by Physics.org, [94] and has been viewed on Youtube over 6,000 times at the time of writing.

Arctic Sea Ice (Digital Version)

Data

Monthly values of Arctic sea ice extent from National Snow and Ice Data Center's sea ice index[95] are used in this composition (figure 4.3). This dataset is a satellite product that tells the extent of sea ice area over the Arctic Ocean, and is described in greater detail in chapter five. This composition uses monthly values of sea ice extent. The biggest signal in this dataset is the seasonal cycle of ice growth and melt. In the spring and summer, sea ice melts and thins. In the fall and winter, it grows and thickens. The extent of winter ice cover has not changed significantly over the period of record, but the summer ice cover has, and so like the Keeling Curve, this dataset shows a seasonal cycle with a multidecadal downward trend.

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[93] Supran, G., et. al., "Assessing ExxonMobil's global warming projections." Science, Vol 378, Issue 6628, 13 January 2023. DOI: 10.1126/science.abk006

[94]Hickey, Hannah, "Listen to the Earth smash another global temperature record." Physics.org, January 19, 2017, Accessed at: https://phys.org/news/2017-01-earth-global-temperature.html

[95] Fetterer, F., et. al., (2017). Sea Ice Index, Version 3 [Data Set]. Boulder, Colorado USA. National Snow and Ice Data Center. https://doi.org/10.7265/N5K072F8. Date Accessed 04-05-2023.

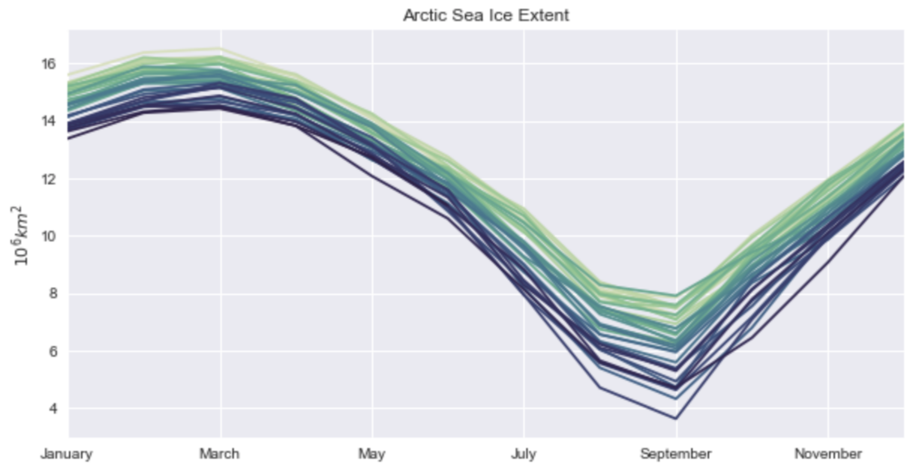

Figure 4.3 Annual cycle of Arctic sea ice extent, each hue represents a different year starting in 1979 (darkest color) and ending in 2017 (lightest color).

Composition Process

My process of working with this dataset was different from the previous two. The Keeling Curve, while taken at a particular location, is considered a reliable measure of the background concentration of carbon dioxide in all of earth's atmosphere. Similarly, GISSTEMP represents a planetary measurement by incorporating measurements from weather and ocean temperatures around the Earth. These connect us to scales that cannot be seen or felt directly with our senses. They are abstract, but real, and to understand them we must develop a planetary perspective. The satellite record of Arctic Sea Ice is not global, though its scale is still larger than anything we can see directly with our senses. Still, this dataset represents a particular ecosystem on Earth, and represents something you can see, feel, hear and touch. It is a place-based dataset.

I had direct experience on the Arctic Ocean as a field technician and ice observer on an international science expedition for the Arctic Observing Network,[96] and this experience shaped

[96] Williams, Bill, and Sarah Zimmermann, "Report on the Oceanographic Research Conducted aboard the CCGS Louis S. St-Laurent, August 1 to September 2, 2013" Joint Ocean Ice Study (JOIS) 2013 Cruise

how I approached sonification. In August when I was there, the sun did not drop under the horizon. The clean sea ice was bright white. When the ice cracked and overturned, bright blue channels of meltwater were visible. Open ocean was dark grayish blue. The colors of the sky were honey-hued or purple when the sun was low in the sky, often gray with clouds, but bright. The soundscape was the rumbling of ship engines and the sound of cracking and groaning ice. Arctic birds visited periodically, and polar bears were sighted, but most of the animals and plants lived under the ice. I was there to take cores of sea ice, to take daily visual ice observations for a prototype ice observing network, and to deploy buoys onto sea ice by helicopter, for modeling purposes.

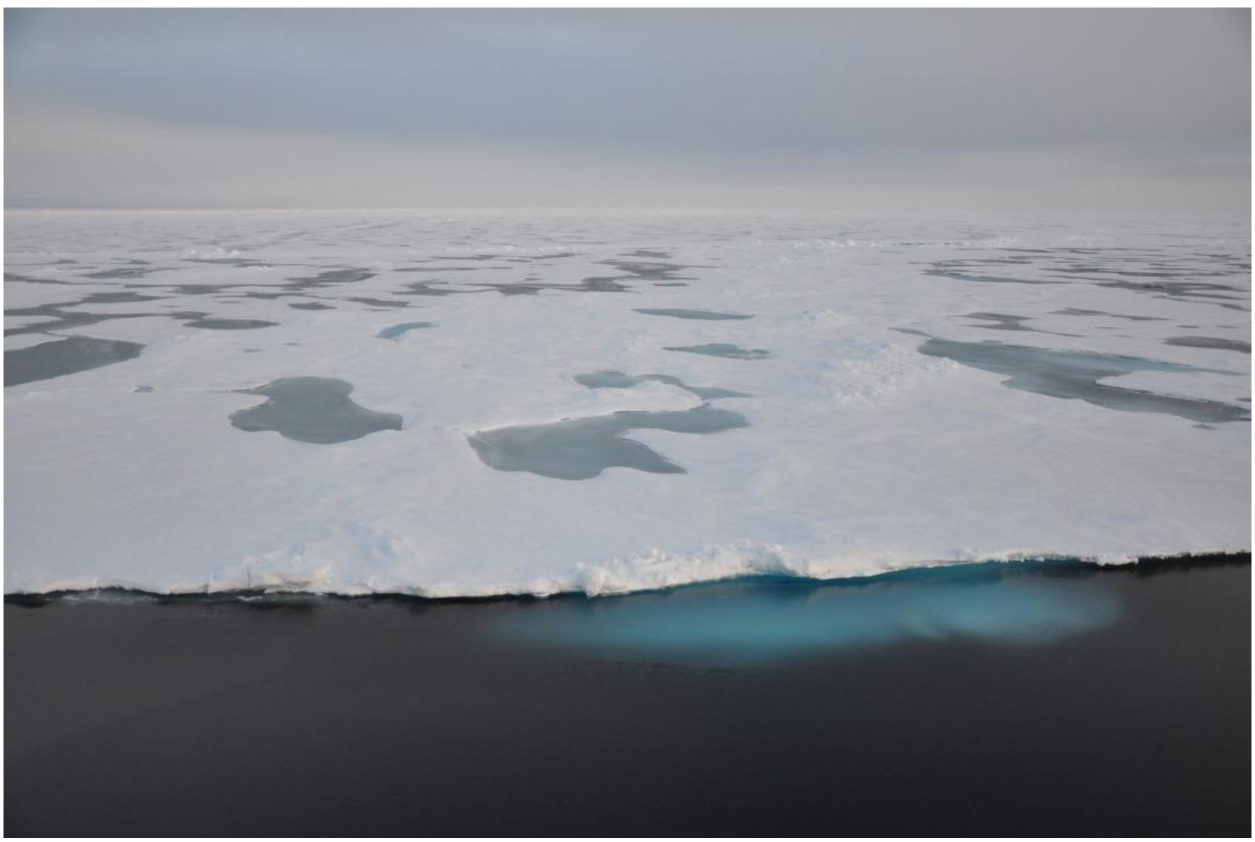

Image 4.1 Photo of sea ice and open water in the Beaufort Sea, taken from the Canadian Icebreaker *Louis S. St-Laurent*, August 2013.

Report, accessed 4/14/23 at:
https://www.whoi.edu/beaufortgyre/pdfs/2013-04%20LSSL%20Cruise%20Report%20v2013-11-29.pdf

My memories of the sounds and sights of the sea ice in the Beaufort Gyre influenced how I approached this digital sonification of the satellite record. Underwater hydrophone recordings of Arctic bowhead whales, made by Kate Stafford, are layered into the sonification, as are recordings of ships, and the sound of waves. These additional sound layers are intended to evoke a sense of the soundscape of the Arctic Ocean, as listeners hear the ice extent waning and waxing with the seasons, and decaying over decades. The monthly sea ice values are sonified in a minor key. The volume of all months in a given year is modified by the severity of the summer melt season. Years with more summer melt are lower volume than the years with more summer ice cover. This effect is tempered by the psychoacoustic phenomena by which our ears perceive higher pitches as louder, even when played at constant amplitude. So when the pitches rise with the growth of winter melt, the human ear perceives them as getting louder even though there is no change in volume between winter and summer.

Reflections

These three pieces were my early experiments in translating data into sound. The datasets could be considered canonical climate datasets: the Keeling Curve shows the undeniable rise in CO_2 from fossil fuel burning, the GISSTEMP temperature record shows warming of Earth’s surface as a result, and the sea ice record shows one of many cascading effects of a warming planet. The first two records – atmospheric carbon dioxide and global mean surface temperature – are both products created from a global network of in-situ measurements. The sea ice dataset is sensed remotely from space, by satellites. All of these datasets describe change of planetary proportions.

Composing with the data changed my relationship to it; it became more than information to analyze. Composing in an artful way was an invitation to consider the context and stories within the data, and to find an emotional tone that feels congruent with my interpretation of the data. It also is a slow process. When experimenting with compositions, I listened to the data over and over again, and each listening experience had a duration that I couldn't rush. This is one of the features of this medium; it takes time. In considering how to understand the magnitude of climate change, Icelandic novelist Andri Magnason writes “Even though I pretend to understand what scientists say — that the glaciers will disappear; even though I read the papers, shut my eyes, and try to picture it all; and even though I see computerized images of the country as it might look when the glaciers recede — I still don’t understand it. I’ve read up on what will happen in other parts of the world if this occurs. Areas where several hundred million people live will possibly become uninhabitable because of water shortage. It hasn't happened yet, and I don’t think I really understand it.” For me, these early works started as attempts to help other people hear and understand the data, but in the process, I realized that I too, like Magnason, was trying to understand what the data means, not as a scientist anymore, but as a fellow inhabitant of a planet under unimaginable transition.

Chapter 5. *Arctic Sea Ice* (2018)

A gestural and sonic interpretation of the satellite record of arctic sea ice, for piano

Arctic Sea Ice is a piece for solo piano performance that expresses the significant decline in sea ice from the satellite record, using both gesture and pitch to communicate this information. It was composed for a presentation I gave at TEDX Seattle, at their invitation to present to a live audience of approximately 3,000 people in McCaw Hall at the Seattle Center.

Data

Monthly values of Arctic sea ice extent from National Snow and Ice Data Center's sea ice index[97] are used in this composition. This index is derived from two satellite products: the Near-Real-Time DMSP SSMIS Daily Polar Gridded Sea Ice Concentrations and the Sea Ice Concentrations from the Nimbus-7 SMMR and DMSP SSM/I-SSMS Passive Microwave Data. In the satellite image, the passive microwave brightness temperature is used to calculate the ice concentration in each grid cell.[98] The sea ice *extent* is the area of ocean covered by ice and the area between ice and open water is determined by the grid cells that have at least a 15% concentration of sea ice.[99]

Compositional Process

The monthly sea ice extent dataset has a strong seasonal cycle. This is because the arctic ocean completely freezes over each winter, and melts back, but not completely, in the summer. This summer melt season has become longer and more severe over the satellite record, but the dominant signal in the record is still the seasonal cycle. In the digital version of this piece,

[97] Fetterer, F., et. al., (2017). Sea Ice Index, Version 3 [Data Set]. Boulder, Colorado USA. National Snow and Ice Data Center. https://doi.org/10.7265/N5K072F8. Date Accessed 04-05-2023.
[98] A grid is a network of intersecting lines over a map or image. A grid cell is the smallest polygon (often a square) of those intersecting lines.
[99]National Snow and Ice Data Center, *Sea Ice Index 3.0 User Guide,* 2008, https://nsidc.org/sites/default/files/g02135-v003-userguide_1_1.pdf

discussed in the previous chapter, I sonified the seasonal cycle. The intention of this piece is not to focus on the seasonal cycle, but rather to highlight the alarming rate of multidecadal decline in sea ice due to burning fossil fuels. To focus on that signal, I subtracted the 1978 - 2010 monthly average sea ice from each monthly data point. The resulting data is the deviation from monthly average, also called the ice extent anomaly, plotted in figure 5.1. This removed the seasonal cycle and shows how the ice extent, each month, compares to its long-term monthly average.

To sonify the sea ice anomaly, I translated the y-axis of this graph to the piano keyboard, so lower and higher values become lower and higher pitches, respectively. One eighth-note represents one month of data, and there are twelve eighth notes per measure. Each measure represents one year in historical time. The 'zero line' is also expressed musically: one hand, the left hand, plays a succession of four chords that hover around the pitch that represents zero sea ice anomaly. These four chords also represent the seasonal cycle, which rises and falls cyclically through the piece. These chords together, with the right hand playing monthly sea ice anomalies, creates a rhythmic structure: one seasonal chord for every three notes of monthly data. Because the left hand is playing chords around the 'zero line,' at the beginning of the piece the right hand is above, or to the right, of the left hand. This is a natural position for the body. As time progresses, the right hand moves down the keyboard, and by the end of the piece, the right hand is continuously crossed over the left hand in a somewhat awkward reach. This gesture adds a visual component to the piece. Not only are the notes representing the data, the performers body also represents the extraordinary changes in the Arctic ecosystem.

The data is mapped to a pentatonic scale spanning five octaves. This scale shifts twice in the piece, each time representing statistically significant shifts in the downward trends of ice extent. The first shift is in the year 2001. This is the year that at least one monthly ice extent trend became statistically significant. The scale shifts again in 2007, because in this year every monthly trend is statistically significant. The year 2012 is also notated on the score because that year's melt season was the lowest on record as of 2018. The anomaly data in figure 5.1 has purple, green, and red colors to show the periods over which the scale shifts to represent the statistical shifts in sea ice extent.

The piece begins with the left hand playing two measures of the seasonal chords before the right hand joins in playing the monthly sea ice anomalies. This allows the listeners to hear the sound and pace of the seasons alone, before adding in the additional layer from the right hand. The music starts with January 1979 and ends in August of 2016 – end of the summer melt season.

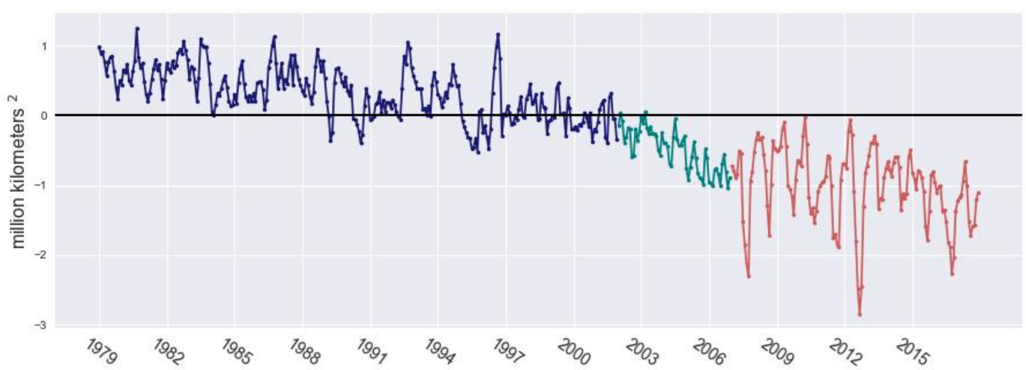

Figure 5.1 Monthly anomalies of sea ice extent over the satellite period. The changing colors show change in statistical significance of the monthly trends, as indicated by a key change in the score.

Figure 5.2. The first three lines of the score of *Arctic Sea Ice.*

The path to composing this process was iterative, and involved feedback regarding playability from Kristina Lee, the pianist who would perform the premier of the piece for TEDx Seattle. I recorded a conversation with Kristina in December of 2018 in which we talked about the process, from the very first draft of the score to the performance itself. Kristina's feedback was especially helpful in determining what octave range was physically feasible and in formatting the score to clarify what is played by the right and left hands. Excerpts of that conversation are printed in table 5.1. Our complete, unedited conversation is included in the appendix.

Judy: *Was the piece/process anything like you expected?*

Kristina: *When Debbie first told me about your work I went to your website and listened to the electronic composition of Arctic Sea Ice (2017), and I thought I was going to play that. When I actually got your score it was completely different than what I expected, and I was delighted.*

Judy: *Why was the piece different than you expected, why were you delighted?*

Kristina: *Because you use an ancient scale, the pentatonic scale, that is very intuitive to the human experience of music, so it was very relatable to me and I knew it would be relatable to the general audience. And you used the time signature that is also ancient…*

Judy: *Yeah, when we first met to talk about the score, I think it was in your studio and I was explaining that each chord is one season and each note is one month and we spent a long time thinking about how to explain this clearly to general audiences. Do you remember that process very much?*

Kristina: *Well you simply explained it to me and it wasn't something that we had to dwell on because it made sense to me right away and when I looked at the music and played the music it was like 'oh yeah, sure this makes perfect sense…'*

Judy: *...because the musical structure is fairly simple, there's three eighths notes to each left hand chord and those are the seasons…*

Kristina*: yeah and that BA-da-da, BA-da-da, BA-da-da, that exists in folk music, that experience of rhythm. Everywhere. Celtic music, Asian music, African Music, Native music, the triple notes are closer to the music that's oral tradition than the double music which is European tradition, the BA-ba, BA-ba, BA-ba. I mean you have the polka and stuff but the BA-da-da, BA-da-da, BA-da-da, that was a baroque dance and a Celtic dance. Korean music* *has that rhythm, you know, so it's interesting to think about the four seasons. The number 12 lends itself to that…*

Judy: *12/8 (time signature)*

Kristina: *Yeah, so it's really interesting to think about your decisions and the decisions that were already made for you, like using the pentatonic scale, and using 12/8, and dividing the seasons. It set up for music that was relatable.*

Judy: *So in my experience as a translator of data and a composer, a term I'm still trying to identify with, it gave me tingle to see the notes expressed by your hands, because all of my other work was electronic music, but this was seeing human gesture as an interpretation of data, and it was intentional to make the gesture uncomfortable or unnatural as the sea ice melts, and the right hand crosses further and further over the left hand. What did that feel like for you, knowing that you are embodying this transition of sea ice?*

Kristina: *The first time we went through the whole thing, yeah it gave me goosebumps, just starting to play it, because there's a storytelling before the piece, so I just found that experience to be just very powerful. The combination of the raw data that you thought through and your work of deciding what kind of music to make out of this, and looking at the score, hearing your story, and then playing, it was a really powerful moment. I knew it was gonna work at that point.*

And, there's an awkwardness to the piece. It's the gestures, you know the reach, but that's in a way not the hardest part because there are overlaps that happen in the first part, because of the seasons and the right hand overlapping with the left hand, but I knew that I needed to bring out the melody which is the data, so there was the awkwardness of trying to execute that within the time, that took some time. How do I make it sound beautiful and haunting while playing every note? Because every note means something here.

So I kept downplaying it like thinking ‘oh it’s not a really hard piece’ because it’s not hard like Rachmanninof with lots of notes played fast, but after playing it I decided that it is a ‘hard’ piece because it is not written with the traditional music composer's approach.

Judy: *Well, and I had to iterate with you, like what's the best way to map this on the score, and your feedback was really helpful in choosing to use the upper staff for the right hand and the lower staff for the left hand, because I made one version of the score that was using traditional notation with the upper staff the treble clef and the lower staff the bass clef and you were like ‘no, this is harder to read!’*

Kristina: *(chuckles) yeah, because I had to fish out the melody in the right hand it was like a treasure hunt finding those notes…*

…that initial part when we were trying to figure out the end result — choosing to tie the repeated notes, where the data didn’t change much from month to month, rather than having a separate note on every single beat had a huge impact. When you decided to hold the repeated notes, that allowed me to start creating phrases and, you know, once I sat, I got the music and I knew what we were doing, I sat down and looked at the music and started singing the melody in my head, like “where do you want to breathe’, where does this data want to breathe when it is musically expressed.

Judy: *... one of the things that makes this really different from writing music and playing music is that, you know, like I basically made a rule, a mapping, and ran the data through that mapping, and I get an output and those are the notes, and I was like ‘here are the notes’ and there was a lot left in terms of the expressivity and phrasing for you to decide, and you did it really beautifully, and those are important questions for the performing artist. You want to express and be true to the data, but there’s still a lot of room for interpretation even staying ‘true to the data’. And that’s one of the exciting things about data sonification. You can make the mapping and then the performer can choose the expressive tone.*

Kristina: *Yeah, and in this case the composition was 100% your work. In the future this could be more of a collaborative work, I mean, but in this case you made all the right decisions. Like the scales you chose. Scale and time signature, the meter. Those were really really smart choices. A scientist who is less experienced about translating this into music, may not choose the best scale, or mode, or meter. Those have such an impact. And because you made smart decisions even though the data doesn't lend itself to musical patterns, I could fish out phrases, and I could rely on them to make musical expressions.*

Table 5.1 Excerpts of a conversation with Kristina Lee and Judy Twedt, December 21, 2018

Performances

The premier performance of this piece was at Seattle Center's McCaw Hall on November 17, 2018. In this presentation, I described my journey into data sonification, motivations for making climate data more emotionally engaging, explained the choice of data and the importance of Arctic Sea Ice on both local and global scales. Then, after a simple explanation of the data mapping, Kristina Lee performed the piece. The explanation included a visual graph of the sea ice anomalies, along with a description of what each hand was playing. Kristina played the left hand seasonal cycle once as I explained the mapping, so the audience could identify the left hand and right hand layers. The talk concluded with a story of the village of Shishmaref, a coastal Alaska Native village that had voted to relocate due to climate change and coastal erosion. The recording on youtube has been viewed approximately 7,100 times as of April 2023.

The piece continues to be played in both private and public performances. Director Henry Hiltner made a video of this piece in performance at the Jack Straw Cultural Center's recording studio which is available on youtube.[100] In June 2019, Canadian Public Radio Host Peolo Pietropailo played this work on his weekly show *In Concert*, in a special segment on music inspired by nature, for an audience of 'hundreds of thousands of listeners.'[101] More recently, it was performed in concert on music for the oceans on Earth Day, 2023 at the National Gallery of Art in Washington, DC.

[100] Available on youtube at: https://www.youtube.com/watch?v=Uzt0qMT5mR4
[101] Email communication from Paolo Pietropaolo on June 18, 2019

Image 5.1 Premier presentation of *Arctic Sea Ice* at McCaw Hall in Seattle, November 17, 2018

Youth Sonification Workshop

In January of 2019, I proposed to Kristina Lee that we offer a youth workshop on climate data sonification held at her piano teaching studio in Bellevue, Washington. She enthusiastically agreed, and so I designed a workshop that would introduce participants to basic concepts in data sonification, and show the connections between math and music. The outcome of the workshop was for students to sonify one or two short datasets using the piano keyboard, and to teach sonification in such a way that no coding would be required. The prerequisites were a basic training in reading western music and familiarity with the notes of the keyboard.

We led two 2.5 hour workshops: one for 8 - 11 year olds, and one for participants 12 and older. The outline and lesson plan for the workshop is included in appendix ii. Participants did a pre and post workshop survey. When asked how they feel about climate change, six students expressed fear, frustration, or sadness. One student had not heard of climate change before, one felt neutral, one did not know how to express feelings in words, one said it feels 'very science-y' and one said it doesn't carry the weight that it should because it's far into the future. Students chose data from a list of cities, and their choices show that a personal connection to the data, unsurprisingly, was important: when asked if students had a connection to the city they chose, eight of eleven students said they had either lived in/near or had family living in their chosen city.

Looking at climate change in different cities helped students understand that some places are warming faster than others:

> " it went down, then it went back up," (11 year old)
> " it stays within the same few keys and jiggles around" (14 year old)
> " it kind of goes up and down, but in the end the pitch really increases" (12 year old)
>
> " My piece jumps around because I assigned each note to a 10th of a degree. However, it increases in the end." (12 year old)

These comments show that the participants were beginning to understand climate variability, and the relationship between weather and climate. They knew that Earth is warming, and they learned, through creating music with annual temperature data for various cities, that the warming is not uniform, and not monotonic.

Over the course of the workshop, students commented on how surprising it was to connect math, science, and music. Undergraduate students also shared this sentiment in feedback surveys (appendix iv), and so I've seen, across a range of ages, the strong degree to which academic skills are compartmentalized into subjects that naturally overlap. A complete outline of the workshop is included in the appendix ii, and this is only one of many ways in which music and climate data can be integrated into formal learning settings.

Conclusion

In this dissertation, this piece is the only acoustic sonification, written as a score for instrumental performance. Unlike the digital compositions, this piece is created anew with each performance and expressive choices of the pianist. Their gestures and choice of musical expression make it a co-creation each time it is performed. The structure is guided by a translation of the graph to the keyboard, with the y-axis of the graph mapped to the length of the keyboard and the left hand cues the listener into the location of the 'zero line.' This is a structure that could be used for other anomaly data sets with strong trend lines, perhaps as a collection of pieces representing different signs of climate change.

A feature of data-driven compositions that are based on time series data is their aging process relative to the historical time they represent. The data evolves with time. At the time of writing, this piece used the sea ice record up to the most recent data release. Now, that data is several years old. The sea ice trend has not changed in any substantial way – it's still declining – and so the underlying meaning of the piece has not changed. But the piece could be updated to include recent years. Perhaps when more time has passed, I will come back to this record and make a new version of this piece.

Chapter 6. *Breathing in a Time of Disaster* (2022)

Context

This collection of sound compositions was created as part of *Breathing in a Time of Disaster,* a mixed media community healing ritual and public art installation. The sound collection is a meditation on the interconnection between the human body and air, and the relationship between the quality of air and the quality of breath. The sound pieces in this collection were made from breath recordings, public health data, and interviews with environmental justice leaders.

The lead artist, Ching-In Chen, began the project while living in Houston in the aftermath of Hurricane Harvey. My involvement in this project came from a lucky encounter. I first met Ching-In Chen at a pre-COVID poetry reading celebrating the release of an audio chapbook "O-Ezekiels' Wife," a collaboration between myself and poet C.R. Grimmer. At the reading, Chen read a poem about breathing in a time of disaster. Immediately feeling the connection between their poetry and its resonance with environmental justice and air pollution, we got talking about a possible future collaboration. At the time, I was a member of a statewide Environmental Justice task force working on a preliminary report which eventually shaped legislation known as the *HEAL ACT,* which defined and established processes around environmental justice in Washington State law. Later, in 2022, Chen reached out to me with an invitation to collaborate on *Breathing in a Time of Disaster* as the sound artist, to compose with breath recordings from participating artists and community contributors. We both felt that the sonification of air quality and public health data would fit well with this project, and so the collaboration began.

The project is influenced by Chen's lived experience with asthma, and also with meditation and breathwork. The participatory project includes pieces created under the theme of public healing rituals from artists in Houston and Seattle. Participants also submitted a one minute recording of breath for use in the composition of a breath chorus, which was my starting point. The purpose of this chapter is to detail the process by which I created the sound compositions that were part of the exhibit.

The project exhibited at Jack Straw Cultural Center in Seattle, Washington October - December of 2022.[102] Public healing rituals in the form of videos, paintings, poems, photographs, etc from contributing artists were featured on two walls of a four-walled gallery through a projector. The rituals were organized by the artists' zip codes. One wall displayed rituals from Houston participants, one from Seattle participants and they were projected concurrently. The exhibit was also interactive: viewers selected a zip code from one or both cities on a touch pad display. This triggered the display of a new ritual and also triggered a zip-code specific sound composition which played along with the public healing.

The exhibit is currently being developed into an online gallery hosted on Omeka. Additionally, the sound collage is available as a guided listening tour. A transcript of the listening tour, which shows how these pieces would be explained for a public audience, is included at the end of this chapter.

Data

These compositions blend both quantitative and qualitative data. Quantifiable environmental and public health data was used algorithmically in the composition process while qualitative data – audio recordings of breath, neighborhood sound walks, and interviews – were used as the primary sound material.

Quantitative Data

In the United States, air quality is monitored by the Environmental Protection Agency and governed by the 1970 Clean Air Act and subsequent amendments. While this legislation has been effective in improving average urban air quality, inequities within urban areas persist and are not captured by the resolution of the existing monitoring stations. Air pollution is highest near the source of emissions, and so neighborhoods near industrial areas, highways, power plants, petroleum refineries, etc., have higher burdens of pollutants. But there simply aren't

[102] https://www.jackstraw.org/exhibit/ching-in-chen-and-cassie-mira-breathing-in-a-time-of-disaster, accessed 5/6/2023

enough air quality monitors to record neighborhood-level differences in air quality within urban areas. Without monitoring these intra-urban discrepancies, the unequal burdens cannot be systematically reduced.

My starting point for Seattle-area data was the Washington Tracking Network's Environmental Public Health Data. The history of this data is noteworthy: it is part of the Washington State Health Disparities map which was a collaborative effort between University of Washington's Department of Environmental and Occupational Health Sciences, Front and Centered (a coalition of communities of color and low-income communities), Washington State Department of Health, Washington State Department of Ecology, and Puget Sound Clean Air Agency. Listening sessions with communities across the state, organized by Front and Centered, informed the development of the map and the types of information that was presented. The health disparities map is now a key resource for state Environmental Justice legislation that was passed in 2021 which required agencies to identify and address environmental health disparities in overburdened communities and underserved populations, and it was developed through a collaborative, community-driven process.[103]

There is no single measurement of air quality. The Clean Air Act requires the EPA to monitor and set standards for ground-level ozone, particulate matter, carbon monoxide, lead, sulfur dioxide, and nitrogen dioxide. When deciding which data to use as a representative of air quality, I chose nitrogen oxides (NO_x). NO_x are a family of chemical compounds that oxidize lung tissue. Short term exposures can aggravate respiratory diseases and asthma attacks. Long term exposure can prevent lungs from developing properly and lead to asthma and susceptibility to respiratory infections. Nitric oxide (NO) is also a precursor to other forms of air pollution including ozone – the primary constituent of smog – and acid rain. NO_x can also alter the balance of nutrients in bodies of water, inducing changes in phytoplankton which can lead to toxic algal blooms. The

[103] In 2020-2021 I was appointed by the Governor to be a member of the Governor's task force on Environmental Justice. This task force produced policy recommendations that guided the writing of the HEAL Act.

EPA uses Nitrogen dioxide (NO_2) as the indicator of NO_x emissions. NO_2 gas gives smog a brownish color.[104]

For the greater Seattle area, we used the *Diesel Pollution and Disproportionate Impact* index from the Washington Tracking Network.[105] This index combines Diesel NO_x emissions with socioeconomic statistics to produce a score for pollution burden and impact that is relative to other census tracts in Washington State. The socioeconomic factors are English proficiency, income spent on housing, education, unemployment, and population living in poverty. The combination of the pollution burden with socioeconomic statistics gives an index about the impact of pollution in a given neighborhood.

For the Houston area, there is no equivalent to the Washington Health Disparities Map. Instead, I used NO_x emissions by census tract, from Demetillo et al.[106] This is a satellite product from the TROPOMI instrument on the Copernicus Sentinel-5 Precursor satellite, from the European Space Agency. TROPOMI is a satellite instrument that monitors the lowest layer of the atmosphere: the troposphere. It takes a picture of Earth every second, with each pixel representing an area of about five square kilometers. Nitrogen dioxide is one of the air quality measurements that TROPOMI records. Demetillo et. al. compared TROPOMI measurements with higher resolution airborne measurements from a NASA field campaign and confirmed that TROPOMI is capable of measuring intra-urban air quality disparities. They also showed that low income non-white residents experience a higher burden of NO_x pollution than higher income white residents in Houston.

Life expectancy, averaged by zip code, was also used for both cities. For the greater Houston area, this data came from *Texas Health Maps;*[107] for Seattle it came from the Washington

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[104] Clean Air technology Center Technical Bulletin "Nitrogen Oxides (NO_x), Why and How they are Controlled, " https://www3.epa.gov/ttncatc1/dir1/fnoxdoc.pdf
[105] https://fortress.wa.gov/doh/wtn/WTNIBL/, accessed 11/10/22
[106] Demetillo, M. A. G., Navarro, A., Knowles, K. K., Fields, K. P., Geddes, J. A., Nowlan, C. R., Sun, K., Judd, L. M., Al-Saadi, J., Diskin, G. S., McDonald, B. C., and Pusede, S. E.: Observing nitrogen dioxide air pollution inequality using high-resolution remote sensing measurement in Houston, Texas, *Environ. Sci. Technol.,* doi:10.1021/acs.est.0c01864, 2020.
[107] https://www.texashealthmaps.com/lfex, accessed 11/10/22

Tracking Network.[108] Life expectancy is "the number of years a newborn can expect to live if the current age-specific death rates remain constant" (ibid). This metric was available by zip code for both cities, and captures the impact of compounding burdens of inequities. In Houston, the average life expectancy from the zip codes of participants varied by as much as 12 years. Unlike the other compositions in this dissertation, the pieces in this collection do not use time series data, which meant that there was no mapping of historical time to musical time. Instead, life expectancy was used as a temporal mapping. This will be described in more detail in the following section.

Qualitative Data

Qualitative data was of three types. The first was breath recordings along with a brief introduction (name, neighborhood) from participants in Houston and Seattle; some of these were recorded by a sound engineer in the recording studio at Jack Straw Cultural Center, others were home recordings. The second was interviews conducted by myself, Ching-In Chen and Cassie Mira with three environmental justice leaders in the Seattle area, and the third was recordings of city sounds, specifically traffic, from Seattle and Houston.

In order to relate the breath recordings with air quality and health data, we needed a common location identifier for each contributor. I chose the zip code, rather than address or census tract. One's zip code does not reveal private information such as address, yet is specific enough to capture gradients in air quality and other health-related metrics. The census tract, another unit I considered, is more meaningful for measuring environmental health disparities and is more demographically homogeneous, however most people do not know their census tract.

[108] Washington Tracking Network, Washington State Department of Health. Web. "Life Expectancy". Data obtained from the Washington State Department of Health, Center for Health Statistics, Death Certificate Data, 1990-2019. Published: February 2020.

The basic adjustments I made to the breath recordings included: noise-reduction and filtering, equalization,[109] and dynamic compression.[110] The background sounds from the recordings on personal devices were so prominent that I did not attempt to filter them out completely. Instead, they became features.

Composition Process

There are multiple types of compositions in this collection. The set of zip-code specific pieces are the only ones that sonify environmental data (see table 6.1). All other pieces in the collection are collages of breath and environmental sounds. I will focus primarily on describing the process of blending recorded material with environmental data for the *Zip Code* pieces, since data sonification is the primary focus of this dissertation.

The creative process started by listening carefully to the breath recordings. This was a meditation in itself: the sound of the breath draws one into an intimate encounter with the body and this primordial process of exchange with the environment. Some of the breaths were barely audible, others were long and smooth and even, and some carried signals of tension in the body. Many of the recordings from Seattle contributors were made in the recording studio at Jack Straw Cultural Center. This meant they were professional quality recordings with little background noise. The recordings from Houston were totally different because they were all made by the participants themselves, in their location of choice and with their recording equipment of choice. Each recording had a unique background noise signature, some with birds and dogs barking in the background, some with traffic noise or the sound of walking. These features of the recordings influenced how I choose to approach the compositions. It's nearly impossible to blend sounds with different background sound levels without creating clicks or other undesirable artifacts, and so I chose not to blend recordings from different cities. This choice flowed well with the physical design of the exhibition: one wall presented art and public rituals from Houston contributors and

[109] Equalization, in audio engineering, is a process of adjusting the gain, or loudness, of different frequency bands.
[110] Dynamic compression, in audio engineering, is a process that reduces the volume of the loud parts of the signal. This is especially important when the primary signal is something quiet like breath. A single loud cough, or a few spoken words, can create a wide dynamic range that isn't conducive for listening to breath, which is the primary signal.

the other wall from Seattle contributors. Only after listening to the recordings did I make choices about environmental and health data.

While listening to the recordings, it became clear to me that I wanted to avoid heavy processing of the breath samples in order to preserve their wholeness. Unlike the other works of data sonification which started with quantitative data and turned that into sound, for this project I was starting with sound samples and shaping them with data. After considering the quantitative data and the breath, I decided to add sounds from the city, specifically from sources of pollution. I recorded a sound walk in Seattle using a Zoom H4n PRoo field recorder and visiting several different neighborhoods on foot and by bus. Artist Melelani Peterson contributed street sounds from three different locations in Houston. For the sounds from each city, I collected 20 - 60 second excerpts and tagged each excerpt by the perceived intensity of the sound – low, medium, or high.

Quantitative data is used in the zip-code specific compositions algorithmically. Each zip code piece starts with the sounds of the city, and the air quality data determines whether to use a low, medium, or high intensity sound. Zip codes with dirtier air start with higher intensity sounds. The piece gradually shifts from the sounds of the city to the sound of the breath. The level of pollution sets the time onset for the transformation from city sound to breath, so in zip codes with cleaner/dirtier air, the breath emerges sooner/later from the pollution source. The total duration of each piece is determined by the life expectancy, with average life expectancy mapped to a 40 second duration and every year above/below the average life expectancy adds/subtracts two seconds from the total duration. In this way, the data is not directly mapped to an audible parameter (i.e. pitch or volume), but instead is used to shape the relationship between sound sources.

Transformation from transportation sound (pollution source) to breath is accomplished by a phase vocoder in Supercollider. The two sound sources, A (pollution source) and B (breath), are converted into frequency-amplitude space with a fast fourier transform, then bins from spectrum B are randomly copied into spectrum A until none of the original bins from spectrum A remain.

When converted and played back into the time domain, the listener hears source A gradually become source B.

Figures 6.1 - 6.3 show the spectrograms of three different zip code compositions. Musical time is the x-axis, sound frequency is the y-axis, and the colors scale represents the sound intensity. In all three cases, the noisy low-frequency rumbling of traffic sounds dominates approximately the first half of the piece, and the breath, which are seen as vertical columns of inhalation/exhalation, emerges from the traffic sounds, but at different times in the composition.

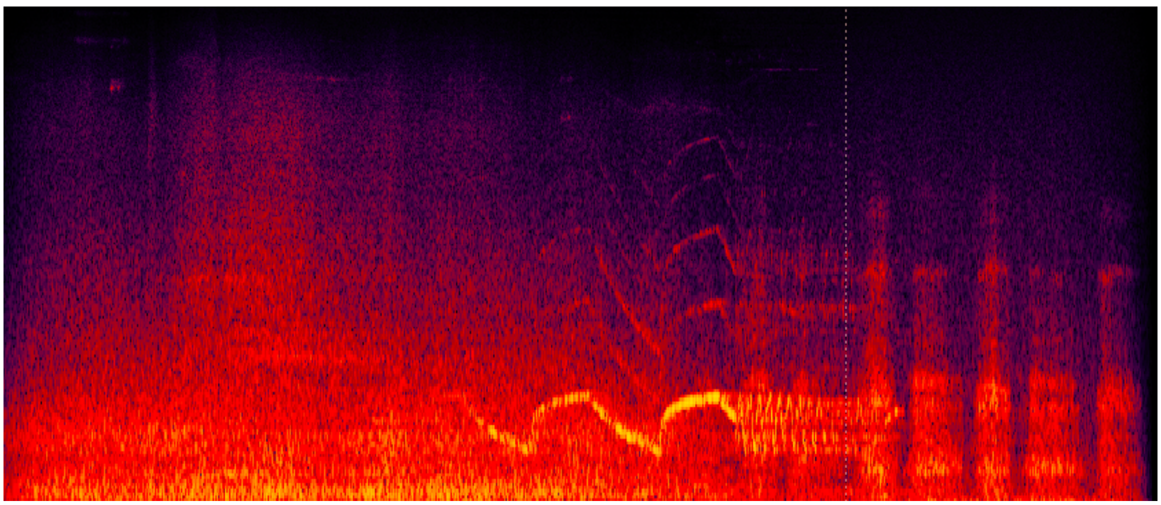

Figure 6.1 Spectrogram fo *Zip Code 98178*

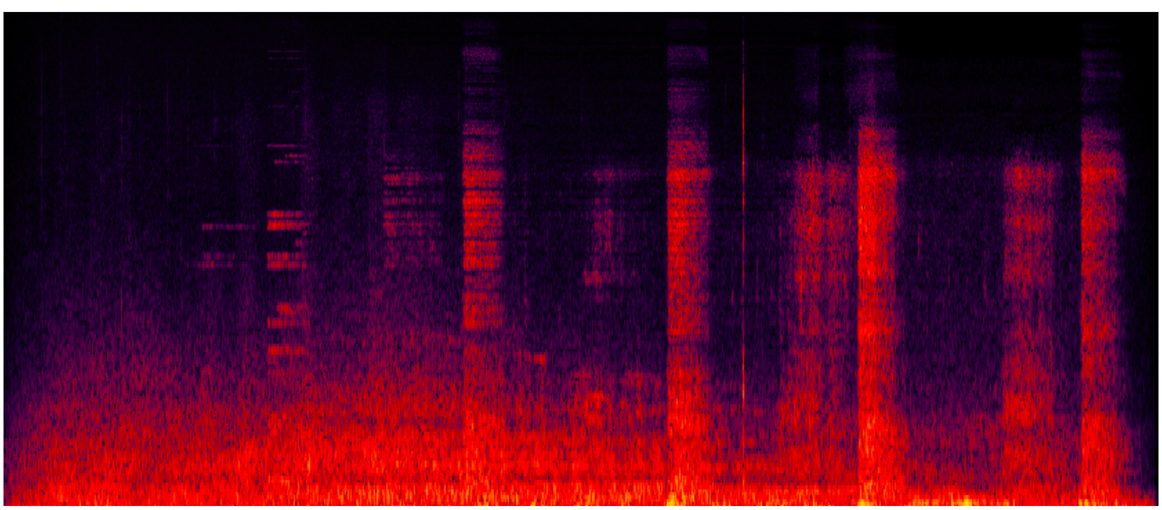

Figure 6.2 Spectrogram for *Zip Code 98502*

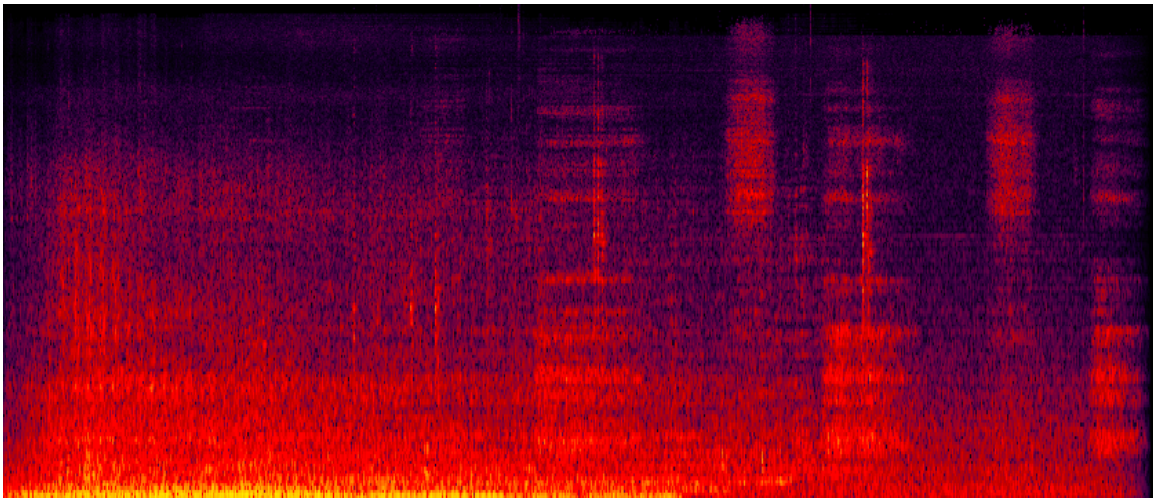

Figure 6.3 Spectrogram for *Zip Code 77012*

The gallery was a rectangular-shaped room, with one wall designated for Seattle and one for Houston. Working with this layout, I composed the pieces for 4-channels, to spatialize the sound and express the spatial heterogeneity of air pollution. The room was rectangular, with speakers aloft in the four corners, as shown in figure 6.4.

The four channel spatial mapping provided another layer of sonification: air quality data was binned into three categories (low, medium and high), and each category was mapped to one of the corners of the room. Each zip code composition began highly localized, in one corner of the room, to emphasize the geographic disparities in air quality. When the breath emerged, it came from all four corners of the room. The breath was not spatially localized in the gallery, but instead heard equally from all speakers, an analog to the body moving through space. When listening to the zip code compositions in series the geographic disparity in air pollution becomes audible within the gallery space.

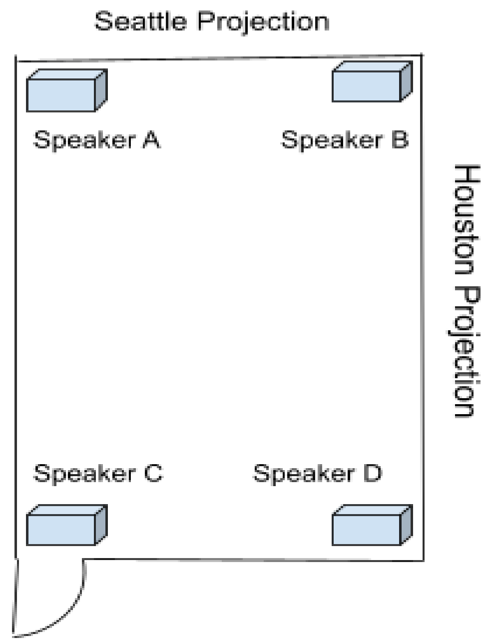

Figure 6.4 Speaker layout in the gallery space at Jack Straw Cultural Center

A small plaque on the wall provided a brief description of the sound compositions for gallery viewers. In the same way that axis labels orient a viewers to a graphical representation of data, a verbal or written description of the composition design orients listeners to the composition as an expression of data and relationships within data.

Composition Name	Quantitative data	Qualitative Data
Seattle zip codes (22)	NO_2, life expectancy	Breath recording, sound walk recording
Houston zip codes (9)	NO_2, life expectancy	Breath recording, sound walk recording
Intro-BeckyAlexander	none	Audio interview
Intro-AngeliqueDemetillo	none	Audio interview

HoustonIntros	none	Recorded introduction
SeattleIntros	none	Recorded introduction
HoustonBreathChorus	none	Breath recordings, sound walk recordings
SeattleBreathChorus	none	Breath recordings, sound walk recordings
Outro_EJLeaders	none	Breath recordings, sound walk recordings, interviews

Table 6.1 List of compositions and the types of data used in the compositions for *Breathing in a Time of Disaster*

Reflection

This collection of compositions stands out in many ways from the other works in this dissertation, not only because they are one piece of a much larger, collaborative multimedia collection, but also because of their use of space and time. In contrast to the other works in this dissertation, this collection does not use time series data,[111] and so there was no temporal evolution or change in the data that created a natural mapping between historical and musical time. Instead, musical time was set by other considerations: the life expectancy of zip codes, the lengths and content of the recorded material, and the design and flow of the installation. The sounds were also site-specifically spatialized, to highlight geographic discrepancies in air quality, however I have also made non-site-specific stereo versions of all of these pieces for the online gallery.

In addition to the spatialization, these compositions are not heard in isolation. Inside the gallery, there are faint sounds of cars passing on the street outside, airplanes flying overhead, people coming in and out of the gallery, and the other pieces that are part of the exhibit, many of which have an audio component that plays concurrently. This adds elements of randomness and

[111] Time series data is simply data that is recorded sequentially, over time.

variation to the listening experience, as the sound compositions are one of many layers of meaning, perspective, and sensory experience.

Chapter 7. *Timescales of Carbon* (2023)

Motivation

How do we orient our lives toward multigenerational timescales?

On December 7, 1972 crew on the Apollo 17 spacecraft took an image of Earth that forever changed our perspective of this planet. The "Blue Marble, " taken 29,000 kilometers from Earth's surface, is one of the most reproduced images in history. This kind of visual imagery of Earth from afar became widely accessible in the second half of the 20th century. Images from spacecraft show vast spatial scales, far beyond what the human eye can see from the ground. One can look at the Blue Marble and know that they are 'in' that image, but imperceptibly small relative to the size of the earth, and thus invisible.

Now let's consider another perspective-altering event: In May of 2008*,* an international team of scientists published results from a multi-decadal ice core drilling program to understand variations in Earth's atmosphere and climate on geological timescales. For the first time in history, we could look back 800,000 years into the carbon record and identify glacial and interglacial events. Comparing the two scales (1:29,000 kilometers versus 1:800,000 years), the ice cores are perspective-altering on another order of magnitude, and represent a paradigm shift in knowledge production. But the data were presented through scientific writing and in graphical charts, and thus has not received as much attention as the image of Earth from space.

This is relevant for climate because the ability to imagine planetary scales is crucial for both understanding and addressing the climate crisis. In the words of sociologist Kari Norgaard, "Imagination is power, especially in a time of crisis. If the broader public cannot imagine the reality of what is going on or imagine the level of change that is needed to change our course, then no forward movement will occur."[112] Photographs of Earth, or of climate-driven devastation, show the spatial magnitude of change and loss, but they do not aid in navigating the temporal

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[112] Norgaard, Kari. "Salmon and Acorns Feed our People: Colonialism, Nature, and Social Action." Rutgers University Press, 2019, pg 239.

scales that our minds must travel in order to grasp the geologic magnitude of climate change. Sabine et. al.[113] write that the temporal dimensions of climate change clash with the timescales on most collective decision-making processes, such as the 2-6 year election cycles and 5-20 year time horizons for community planning and cost-benefit analysis, and Richard Dawkins notes that "our brains evolved to deal with problems within the orders of size and speed which our bodies operate at."[114] These timescales do not support actions whose consequences will be felt 20 or more years into the future. The human brain evolved to respond to immediate and direct dangers and rewards.

Image 7.1 Earth, seen from the Apollo 17 Spacecraft on December 7, 1972. This image is known as the "Blue Marble."

[113] Pahl, Sabine, et. al. "Perceptions of time in relation to climate change." WIREs Clim Change 2014, 5:375–388. doi: 10.1002/wcc.272.
[114] Dawkins, Richard. "Why the Universe Seems So Strange." TED Talk, 2006.

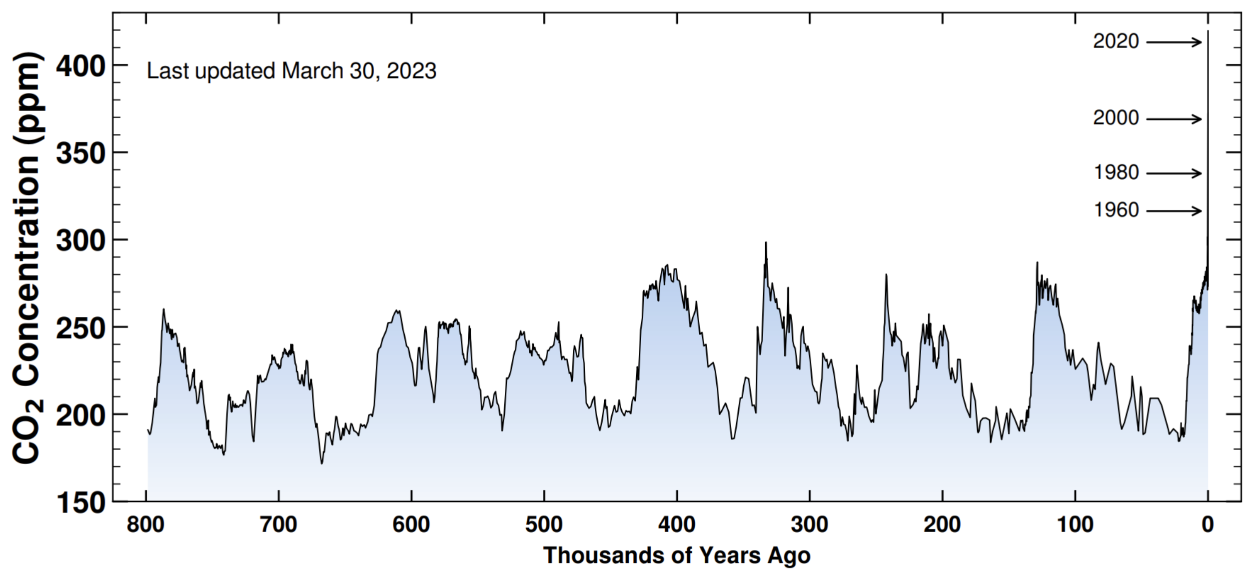

Figure 7.1 Carbon Dioxide from EPICA Dome C[115] as presented by the Scripps Institution of Oceanography at UC San Diego

My motivation in creating a collection of pieces that focus on different timescales of the atmospheric carbon record is to create an experience for listeners to be able to foreground and grapple with rates of planetary change. By listening to change on a range of different scales, we bring the temporal dimension of climate change into focus, and create an opportunity to reflect on the discrepancy between the timescales which dominate our attention and the timescales over which climate disruption unfolds. I used atmospheric carbon dioxide as the indicator of climate for several reasons: it is closely correlated with global mean temperature over geological time, it has both seasonal and orbital cycles, and because high quality measurements that span many different timescales are available thanks to decades of scientific research and international collaboration.

The CO_2 records in this collection are in situ[116] atmospheric CO_2 and proxy measurements from Antarctic ice cores, which go back 800,000 years before present. The scales range from weekly averages from the in situ measurements to thousands of years from the ice core data. While these

[115] Lüthi, D., et. al. "High-resolution carbon dioxide concentration record 650,000-800,000 years before present." Nature, Vol. 453, pp. 379-382, 15 May 2008.
[116] *In Situ* means that the data is measured in place, adjacent to the instrument, and not from afar (such as a satellite or ice core).

are all extremely short timescales compared to Earth's 4.6 billion year history, they are the scales relevant to understanding contemporary climate change.

There are four digital sound pieces in this collection, starting with the most recent records and shortest time scales, and ending with the longest records and longest timescales. Data, motivation, and compositional methods are explained for each piece, as well as a description of their premier performance at the Vashon Center for the Arts on May 12th, 2023.

Compositions

i. *In Situ 1988, In Situ 2014*[117]

Data

Data for *In Situ 1988* and *In Situ 2014* is from the National Oceanic and Atmospheric Administration's Mauna Loa Observatory in Hawaii, maintained by the Scripps CO_2 program.[118] Weekly and monthly in situ CO2 records were downloaded from the Scripps CO_2 website[119] in January 2023.

Motivation

The motivation behind these pieces is to listen to annual and sub-annual variations in CO_2, and to recognize that the slow rise in CO_2 cannot be easily discerned when listening on weekly and monthly timescales. Like the ups and downs of human social life, CO_2 wobbles around week to week, and follows the breath of the seasons: a seasonal rise in atmospheric carbon in the winter and spring months as photosynthesis slows down for the season, and a seasonal decline in atmospheric carbon in the summer and fall months, following the increase in photosynthesis due to increased seasonal sunlight.

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[117] Twedt, Judy (2023), Timescales of carbon: In Situ 1988, In Situ 2014, Dryad, Dataset, https://doi.org/10.5061/dryad.f7m0cfz1v

[118] C. D. Keeling, et. al. "Exchanges of atmospheric CO2 and 13CO2 with the terrestrial biosphere and oceans from 1978 to 2000." I. Global aspects, SIO Reference Series, No. 01-06, Scripps Institution of Oceanography, San Diego, 88 pages, 2001.

[119] https://scrippsco2.ucsd.edu/data/atmospheric_co2/mlo.html, accessed 5/6/2023.

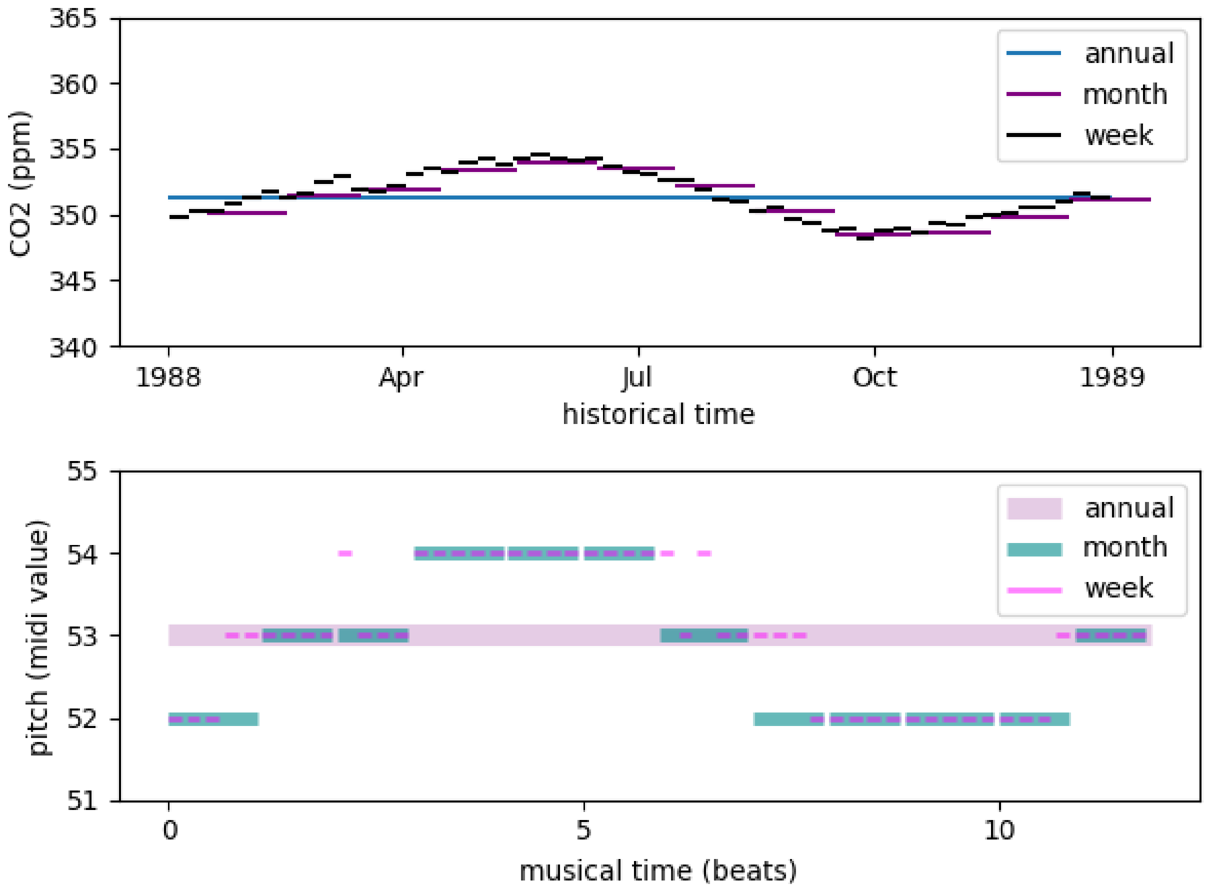

Figure 7.2 Comparison of the *in situ* carbon dioxide values (above) with their mapping pitch and musical time (below).

I chose to make two pieces with the *In Situ* record, so that the main features of each individual piece are weekly and monthly variations, while the juxtaposition of the two pieces, i.e. listening to one right after the other, highlights the dramatic increase between the two dates. It's only when hearing one after the other does the rise in CO_2 become obvious. The two pieces are close enough together that they fit within a human lifespan. The start year 1988 was chosen because that is the year when CO2 reached 350 parts per million (ppm). The year 1988 is also when NASA scientist James Hansen briefed congress on the dangers of the rampant rise in CO_2, and warned, controversially, that global warming could already be detected in temperature records. In 2008, Hansen et al. argued that if "humanity wishes to preserve a planet similar to that on which civilization developed and to which life on Earth is adapted, paleoclimate evidence and ongoing climate change suggest that CO_2 will need to be reduced from its current 385 ppm to at most 350 ppm, but likely less than that," and this number became the name of the network of climate actions groups known as 350.org.[120] For these reasons, I chose 1988 as the starting year for the first composition. The second *in situ* composition sonifies data between 2014 - 2018, a window of time in which CO2 rose above 400 ppm. While 400 ppm is not scientifically significant, it was a useful turning point for science communication and public reflection on the ongoing, and rapid, rise in this potent greenhouse gas.

Process and aesthetic considerations

The data is mapped to a 12-tone equal-temperament scale spanning three octaves, with 340 ppm and 420 ppm as the lower and upper limits of the data range. In this mapping, 340 ppm is sonified as 130.81 Hz, and 420 ppm is sonified as 1046.50 Hz. For these pieces, I wanted the sonic familiarity of an equal-temperament scale, so I chose a 12-tone scale to maximize the number of frequency bins (36 in total) within a relatively narrow range.

Each of these pieces sonifies five years of data at three different overlapping resolutions: weekly, monthly and yearly. Mapping of a sample year (1988) is shown in figure 7.2, with the original data in ppm and historical time above and the data mapped to pitch and musical time below. The choice to map from ppm to a 12-tone scale reduces the resolution of the data and creates more repetitive pitches, which creates a more rhythmic effect. Five years of the historical record, which is used in these pieces, is enough to hear the rise in CO2 if paying close attention, but it requires concentrated effort. The main effect is to hear the interplay between weekly and monthly carbon fluctuations. I also wanted the pieces to be one or two minutes long – the shortest duration of the whole collection – and to be played one right after the other. I experimented with tempos and found that a tempo of one monthly data point per every 1.2 seconds moved at a pace that felt unrushed but fast enough for the seasonal cycle to be recognizable.

[120] Hansen, J., M. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos, 2008: Target atmospheric CO2: Where should humanity aim? Open Atmos. Sci. J., **2**, 217-231, doi:10.2174/1874282300802010217.

Each of the three timescales of data are sonified by a unique instrument. Since the motivation of these pieces is to hear the relationship between the three different timescales, I chose simple percussive sounds to accentuate the rhythm of the temporal ratios. The beat represents one month, and there are four or five weeks per each month. A long-reverberation bell sound represents the annual data, as a background sound. The synth playing this annual CO2 was modeled after a recording of a Tibetan prayer bell.[121] It consists of a bank of twelve frequency resonators excited by an input frequency and low-pass filtered pink noise. The input frequency is the mapped annual CO_2 value, shifted down one octave. The synth playing the monthly and weekly CO_2 is modeled after a mallet. It's also composed of a bank of eight frequency resonators that are excited by pink noise. The fundamental frequency is given by the mapped CO_2 value. The difference in sound between the weekly and monthly values is determined by the decay length of the ring times for the resonators. The decay length of the monthly values is twice as long as the decay length for the weekly values.

The choice of percussive instruments modeled after a bell and mallet was to create a minimalist sound that lets the listener hear how different the carbon record sounds when we pay attention at weekly, monthly, annual, and decadal timescales. These compositions could readily be written as a score for live performance, as well.

ii. *Holocene*[122]

Data

Holocene sonifies data from the Law Dome ice core[123] for years 1 CE to present, and Epica ice core[124] of years 8000 BCE to 1 BCE. Both of these ice cores are from Antarctica, and are significantly correlated with Antarctic temperature.

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121 Acoustic modeling by Elic Sluyter: http://sccode.org/wondersluyter, accessed 5/6/2023.
122 Twedt, Judy (2023), Timescales of Carbon: Holocene, Dryad, Dataset, https://doi.org/10.5061/dryad.hqbzkh1mp.
123 Rubino, Mauro, et. al. "Law Dome Ice Core 2000-Year CO2, CH4, N2O and d13C-CO2". v1. CSIRO. Data Collection. https://doi.org/10.25919/5bfe29ff807fb.
124 Lüthi, D., et. al., 2008.

Motivation

The Holocene is a geologic epoch that began approximately 11,700 years ago as the last glaciation ended. This is the epoch in which human civilizations flourished. At the onset of the Holocene, atmospheric carbon dioxide concentrations were approximately 265 ppm, and they remained below 280 ppm until the 18th century and the beginning of the industrial revolution. Compared with this record of orbitally-driven changes in CO_2 in the previous geologic epoch, the recent rise in CO_2 is extremely rapid and extremely high. At the time of writing, a working group within the International Commission on Stratigraphy is deliberating to determine when to formally recognize the end of the Holocene and the beginning of a new geologic epoch, the Anthropocene.[125] Some scholars have raised important objections to the term 'anthropocene,' and have suggested other names.[126] I use the term *anthropocene* because that is the term discussed by the working group within the international commission on stratigraphy.

This *Holocene* composition creates an experience of listening to the comparatively stable climate of the Holocene epoch, and hearing the end of the Holocene and the beginning of the Anthropocene.

Composition Process

A key compositional choice I faced with this data set was how to map historical time to musical time. The carbon record was relatively stable for ~97% of the historical period. I considered a linear mapping of historical to musical time, but if the composition was, say, five minutes long, the rise in carbon would occur in the last nine seconds of the piece. For four minutes and fifty one seconds the listener would hear a steady sound, which is musically uninteresting and risks quickly losing listeners' attention. To address this challenge of sonifying a hockey stick-shaped carbon record, I made two compositional choices. The first choice was using a nonlinear representation of time and a steady tempo, and the second is the use of a short, repeated melody to create musical structure. I'll explain the melody and its mapping first, then explain the nonlinear mapping of historical time to musical time.

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[125] http://quaternary.stratigraphy.org/working-groups/anthropocene/, accessed 5/6/2023.

[126] See, for example: Donna Haraway, "Anthropocene, Capitalocene, Plantationocene, Chthulucene: Making Kin." *Environmental Humanities* 1 May 2015; 6 (1): 159–165. doi: https://doi.org/10.1215/22011919-3615934.

The *Holocene* melody is three measures long, each measure is a three-tone sequence with scale degrees: [3,1,3], [3,3,5], [3,3,8], as pictured in figure 7.3. Each measure (the sequence of notes between the vertical bars) corresponds to one data point, and the pitch for all notes in the measure are determined by the mapped carbon midi value, so that repeated CO_2 midi values create a repeating melody. When the CO_2 value shifts up or down, the whole measure shifts by the same degree, preserving the interval between notes. This way, the melodic structure stays the same, but is translated up or down the scale according to the carbon record. The CO_2 value in ppm is mapped to a pentatonic (five-note) equal-temperament scale spanning six octaves, from 392 Hz to 5587.65 Hz. This pitch value determines the pitch of the first note in each measure. The other two pitches in the measure are determined in relation to the first pitch, by the aforementioned scale degrees.

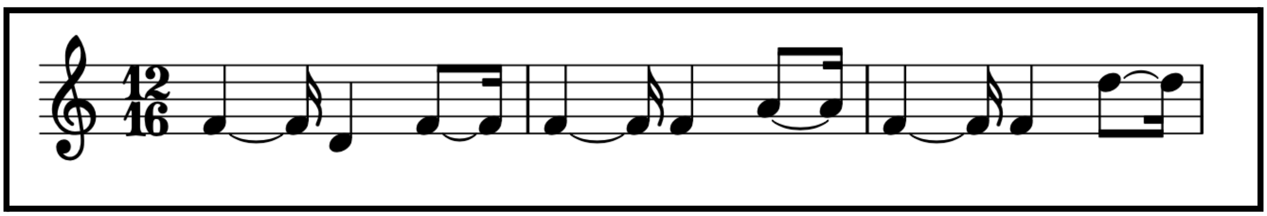

Figure 7.3 Melodic structure of *Holocene*

The mapping of historical time to musical time is enumerated in table 7.1; in the first 70 beats each beat represents 75 historical years. Then, this shifts to 50 historical years represented per beat for 63 beats, and gradually reduces to 1 historical year per beat. This has the advantage of creating more musical time to listen to the anthropogenic rise in CO2 while limiting the overall length of the piece. This was important to me, as this composition is intended to be heard side by side with other pieces in the collection, and I wanted the durations to be relatively short, approximately five minutes. For a public audience, I describe this time mapping with a flip-book analogy. Early in the composition, pages are metaphorically flipping quickly but slow down over time until we see one page at a time at the end. Figure 7.4 shows the original carbon record series in historical time (above), and the carbon record mapped to pitch and musical time (below). This nonlinear time mapping stretches out the recent rise in CO2 relative to the stable period.

To remind listeners that historical time 'slows down' as musical time progresses, this piece includes a digital instrument that plays the number of historical years represented per beat. The sound is a simple thud sound made with FM synthesis. For the first three intervals (75, 50, and 25 years per beat), the instrument sounds like buzzing. This is because percussive sounds played above approximately 20 Hz are indistinguishable as separate events to the human ear. When the time interval reaches 10 or fewer historical years per beat, each individual thud sound is audible and becomes rhythmic.

Table 7.1 Mapping of historical time to musical time (in beats) in *Holocene*

Historical years represented per beat	Number of beats at this rate	Historical time period represented
75	70	8,000 - 2750 BCE
50	63	2750 BCE - 400 CE
25	59	400 - 1875 CE
10	10	1875 - 1975 CE
3	12	1975 - 2011 CE
1	11	2011 - present

iii. *Glaciations*[127]

Data

The records used for this piece are the Law Dome ice core[128] for years 1 CE to present, and Epica ice core[129] for years 800,000 BCE to 1 BCE, spanning eight complete glacial cycles.

[127] Twedt, Judy (2023), Glaciations, Dryad, Dataset, https://doi.org/10.5061/dryad.kwh70rz8j
[128] Rubino et. al., 2019.
[129] Lüthi et. al,. 2008.

Motivation

This composition works with a much larger scale of time: 80 times longer than the *Holocene* composition. This scale encompasses the small shifts in earth's orbit which scientists believe drove the rise and fall of eight successive ice ages and alternating warm periods. The relatively high level of atmospheric CO_2 which characterizes the Holocene was typical of interglacial periods: over the last half a million years, Earth experienced four full glacial/interglacial cycles. During each warm interglacial period, the amount of atmospheric CO_2 was approximately that of the Holocene epoch. These glacial/interglacial cycles are driven by changes in earth's orbit, affecting the amount of sunlight received by the earth, which subsequently affects climate and carbon cycling.

The intention behind the compositional choices in this composition is to evoke a sense of vastness and wonder, and to create a sonic landscape of planetary motion and deep time. Although the present carbon record is included and adds an element of alarm, historical time is not stretched to draw out the recent anthropogenic rise, as it is in *Holocene*. The cycles of the ice ages take center stage in this piece.

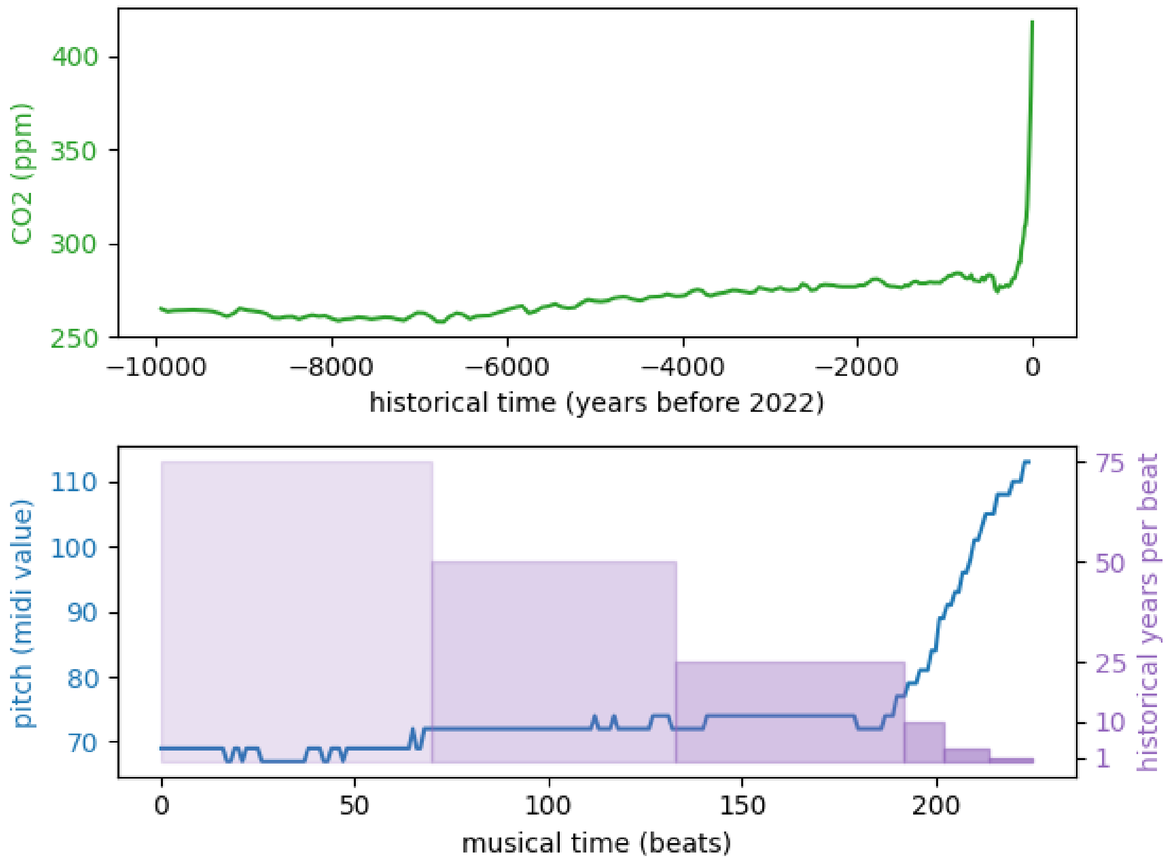

Figure 7.4 Carbon dioxide values mapped to a linear timeline (above) and carbon dioxide values mapped to pitch and musical time as the blue line (below). The purple bars show how many historical years per beat are mapped to musical time.

Compositions Process

The glacial cycles are the central organizing feature of this composition. Historical time is linearly mapped to musical time: one beat in musical time represents 2000 years. The carbon record is mapped to a pentatonic scale spanning six octaves, with 170 ppm and 420 ppm at the lower and upper limits, respectively, of CO_2 measurements.

A simple sine wave tone glides up and down to sonify CO_2. This is visible in the spectrogram (figure 7.5) as a bright yellow line. Three additional longer sonic layers rise and swell with each successive interglacial warm period, all using FM synthesis. One layer is a beating sound, with three or four beats per data point. This sound was inspired by Barry Truax's *Solar Ellipse*, as a sound of orbital motion. The carrier frequency of this sound is set by the first value of CO_2 in the cycle, and stays constant for the duration of the cycle. On the spectrogram, this layer appears as a parallel horizontal line over each glacial cycle, in a pyramid shape, with higher frequencies audible at the peak of the interglacial period. A second layer is sustained over three data points, or approximately 6,000 historical years. This sound is created with complex modulation FM synthesis. The carrier frequency is one octave below the CO_2 value. These appear as box-shaped notes in the spectrogram. A third sound is held over the duration of the whole glacial cycle. This is made with a complex carrier frequency set, as with the first layer, by the first CO_2 value in the cycle. These notes are visible on the spectrogram as diamond-shaped sounds with the largest frequency range.

The final data point, which represents the present day CO_2 concentration, is held longer than the others, and fades away. This was an aesthetic choice not to cut off the sound too abruptly, but allow the high frequency. It is an absurd, almost a comical sound in contrast to the rest of the piece, intentionally disjointed.

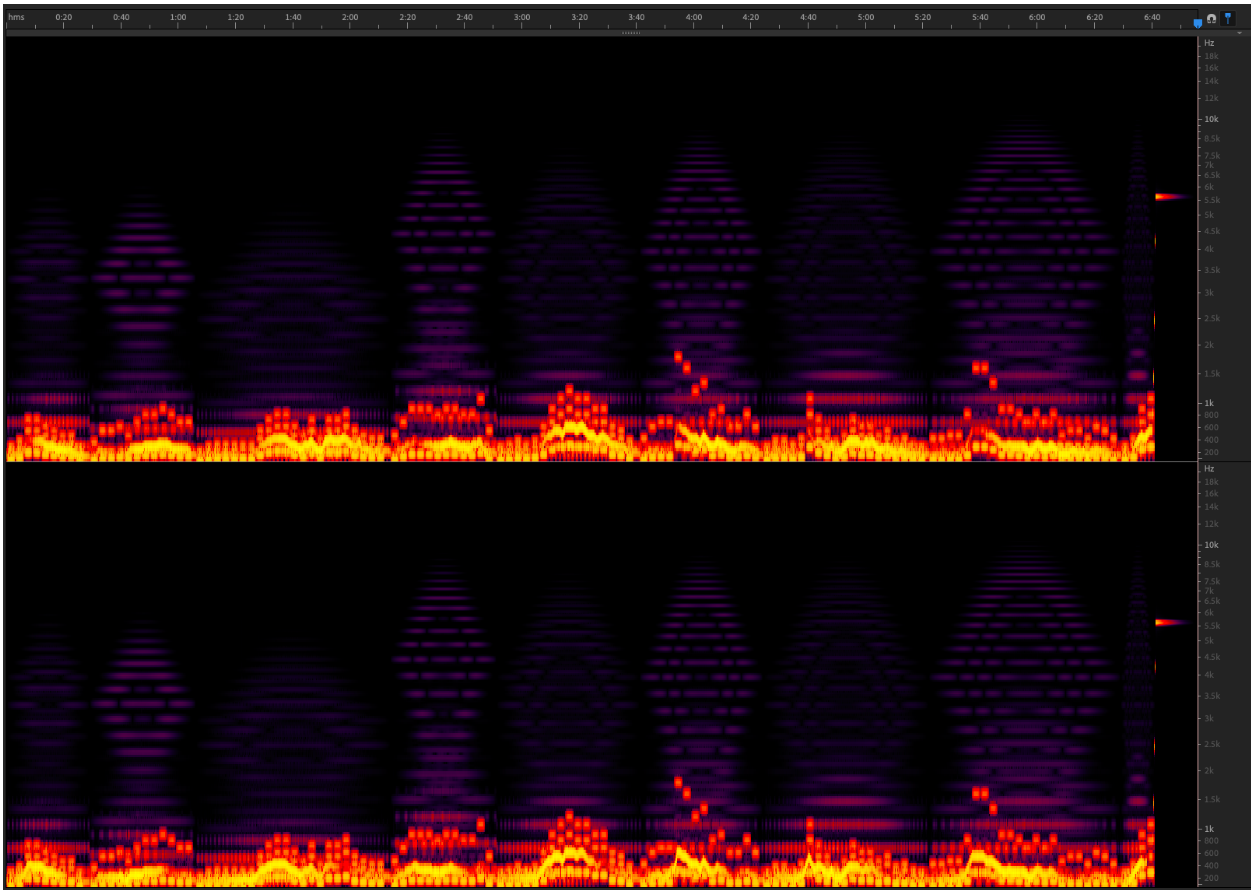

Figure 7.5 A spectrogram of *Glaciations,* showing acoustic frequency across time for left and right channels (top and bottom).

Performance and listener feedback

This collection of pieces premiered at the Vashon Center for the Arts in the Kay White Auditorium on March 14th, 2023 in a combination performance and talk. The question framing this collection of pieces was and is: "How do we orient our lives toward multigenerational time scales?"

The order of presentation started with the shortest time scales and most recent record (*In Situ 1988* and *In Situ 2014)*, followed by *Holocene* and ending with *Glaciations*. I explained and described the sources of data (in situ weather station measurements and ice cores proxy records), and before the performance of each composition, I updated a physical timeline that spanned the width of the stage as yet another way for the audience to understand the different timescales. I explained that the length of the stage would represent a timeline, with the present year on the far right, delineated with a large sign. The year that the composition started (in this case, 1988), was the other end of the timeline, delineated also by a large sign that rested on a stand next to the podium. After introducing *Holocene*, I updated the timeline by physically moving the sign that said '1988' to the other side of the stage and placing it behind the sign '2023' and updating the beginning of the timeline with the new start date. I did this again after introducing *Glaciations*. This way the audience had a visual anchor which showed that the timescale of the previous piece was a tiny fraction of the timescale of the current piece (figure 7.6).

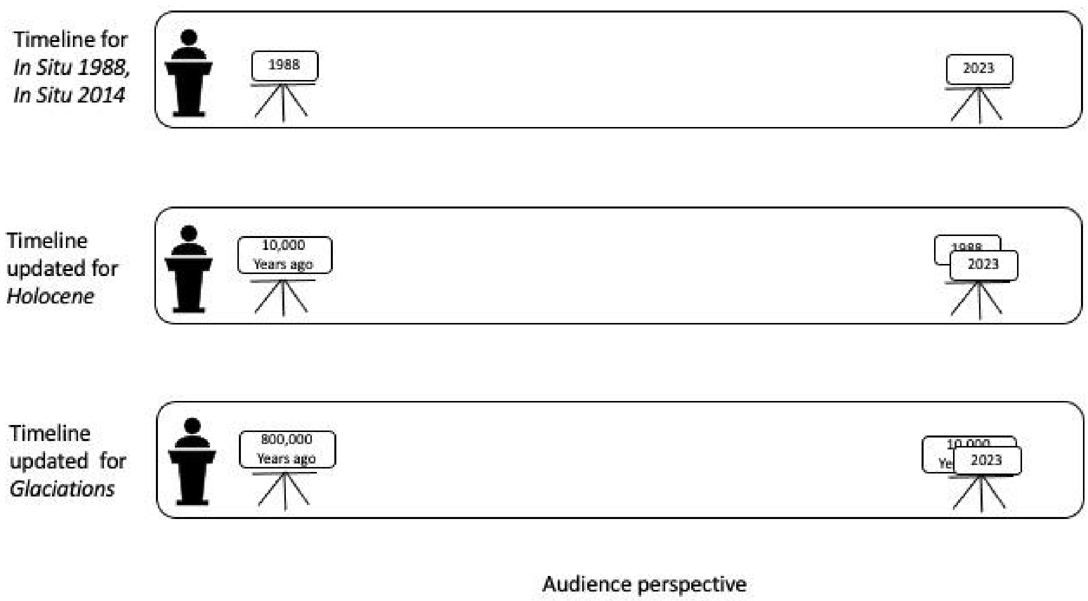

Figure 7.6 Visual timeline, updated for each consecutive composition, in the 4/12/23 performance of the Timescales Collection.

To aid in the interpretive aspect of the listening experience, the audience heard short samples of instruments in each piece before playing the whole composition, to identify different compositional layers. It's the sonic analog to explaining axis labels or a legend when presenting data graphically, and is an important part of the presentation of sonifications. Before listening to the *In Situ* pieces, the audience heard ~ 10 second snippets of each digital instrument by itself, one playing the weekly data, one playing the monthly data, and one playing the annual data. This part of the presentation is important in sonifications. Before playing *Holocene*, the audience heard a sample of the percussive instrument which sonified the number of years passing per beat, and before listening to *Glaciations*, the audience listened to a short sample from each of the four compositional layers in that piece. Visual graphs of the data were shown after the performance of each piece.

To conclude the event, I invited the audience to collectively improvise a song of the future, to make ‘climate jazz’. This experiment had three intended outcomes. First, to bring some physical movement and energy into what was otherwise a sedate listening experience. Second, to highlight that our actions, individual and collective, shape the future; and third, for the audience to practice doing an unfamiliar collective experiment in a low-risk setting.

Audience members were asked to choose from one or more of five different percussive sounds that could easily be made with hands, feet, or a piece of paper. The sounds were imbued with meaning by presenting a map of these sounds to five different human activities that promote resilience and ecological stability (table 7.2). These sounds and their mapping were explained, demonstrated, and written on a slide for visual reinforcement. The timing was structured with a simple series of slides that showed decades 2030 through 2100 in large font, one for each decade. The guidelines were that people could play as many instruments at a time as they wished, and could switch instruments as often as they liked. As I was describing this, one audience member gave an energetic hoot.

Table 7.2 Sounds that the audience used to improvise climate jazz

Instrument	**Mapping**
Hand clapping	Clean transportation
Hand ‘washing’ (rubbing hands together)	Ecological education
Finger snapping	Regenerative food systems
Feet tapping	Justice for people, plants, and animals
Paper flapping	Wind, solar, and other clean energies

To start, I did a short countdown and the audience began as I displayed the first '2030' slide. The audience made a great cacophony of rhythms and sounds, and as the decades progressed, I raised my hands in the air to suggest the audience raise the intensity, and they did. We moved quickly through the slides, so the whole experiment lasted not more than one minute, and transitioned into an applause.

Approximately 75 people were in the audience, and 32 voluntarily submitted feedback. The question was "What did these compositions evoke for you?" The responses which answered that question in a personal way were:

- "Highest piercing tones were frightening"
- "Lowest tones recall elephants and whales"
- "Anxiety, panic..thanks for the idea of hope for the future"
- "Anxiety"
- "I <u>felt</u> the information in a different place in my body"
- "I teared up…curiosity, hope, discomfort"
- "Frightening"
- "Rising sense of alarm..incredibly powerful"
- "Feeling concern for my grandchildren and future generations"
- "Beauty, sadness, alarm…*Glaciations* sounded like whale songs"
- "Glaciations reminded me of whale song"
- "Frightening"
- "Alarm, urgency'
- "Shocking and heartbreaking"
- "Interesting to see *and* hear"
- "Very anxious when sound went faster"
- "My body felt comfort in the sound of glaciations…I could really feel the contract in my body of CO2 levels rising – a quickening of heartbeat, a tensions rise, anticipation and anxiety"

➢ “I felt oddly uplifted”

Reflections

This collection is longer than the others; it belongs in a 30-60 minute presentation with a description of the data sources and the compositional choices. Unlike the short music video *The deafening rise of carbon pollution* (chapter four) which also sonifies the carbon record and has been used widely in classrooms, this collection is unlikely to be added into an existing talk or lesson on climate change. It needs more time to be presented.

While working on these pieces, I experienced an evolving relationship with the year 2100. This year in the future has no geophysical significance, but has been adopted in the scientific community as a common ending-year for climate model simulations. When I started graduate school, the year 2100 felt very distant. Now, it is the year in which my toddler will, hopefully, turn 79 years old. I wonder: How will she relate to the larger-than-human world? How will she cope with wildfires, drought, the rise in infectious disease? How will she relate to the mass migration of humans who become climate refugees? Will she become one herself? Composing these pieces, stretching the focus of my time horizons, has brought the future into the present in a new way for me, as I think about how her early childhood experiences, which I am actively shaping, will stay with her into a future far beyond my lifetime.

Journal entries from August 2022, when I began these compositions, include the following questions:

> *How shall we listen to the onset of an ice age? To the melting of an ice age?*
>
> *Shall historical time go forward, or backward?*

I chose to compose the pieces such that historical times goes forward as the musical time unfolds, but the intended presentation order of the pieces moves progressively back in time, and lengthens. In this way, the temporal perspective gradually widens while the orientation toward time (moving forward toward the present) stays the same. Each piece brings the listener back to the present; the place where we touch the future.

Chapter 8. Conclusion

Sustaining Attention in a Culture of Distraction

> "What determines what we remember and what we forget? The key to memory consolidation is attentiveness. Storing explicit memories and, equally important, forming connections between them, requires strong mental concentration, amplified by repetition or by intense intellectual or emotional engagement."[130]

Nicholas Carr is a writer whose work focuses on the intersection of technology, culture and commerce. His book, "The Shallows: What the Internet is Doing to our Brains," in which the above quote was written, surveys research in psychology and neuroscience to show how the rapid consumption of online digital information reduces our capacity to turn information into knowledge. Sustaining attention is necessary not only for forming long term memories but also for generating emotions linked to moral sensibility such as empathy or admiration.[131] These emotions take longer to form in the brain, and subsequently last longer. "If we're unable to attend to the information in our working memory," Carr says, "the information lasts only as long as the neurons that hold it maintain their electric charge – a few seconds at best. Then it's gone, leaving little or no trace in the mind."

One of the experiments Carr describes was conducted by Mary Helen Immorino-Yang and other researchers at USC's Brain and Creativity Institute. Subjects in the study listened to stories designed to evoke admiration or compassion. Through fMRI brain imaging, they found that while the brain reacts quickly to stories of physical pain – a bodily injury, for example – stories of psychological suffering took longer for the brain's empathy response to form and involved more introspective processing. Listeners needed more time to form emotional reactions to stories of non-physical pain or to stories of virtue and skill. Neither this study nor Carr's book mention climate change, but these discussions of attention, memory, and emotion are nonetheless relevant

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[130] Carr, Nicholas, *The Shallows: What the Internet is Doing to our Brains.* Norton, 2020.
[131] Mary Helen Immordino-Yang, et. al., "Neural Correlates of Admiration and Compassion," *Proceedings of the National Academy of Sciences,* 106, no 19 (May 12, 2009): 8021-26.

to understanding the relatively slow timescales of droughts, sea level rise, and other climate disasters.

Many of the compositions I've presented here are intended to draw our focus to the multi-decadal and longer timescales of climate change. Rob Nixon, a professor of environmental humanities, defined the timescales of climate disaster in his book "Slow Violence and the Environmentalism of the Poor." Slow violence, he says, is a type of violence that "occurs gradually and out of sight, a violence of delayed destruction that is dispersed across time and space, an attritional violence that is typically not viewed as violence at all." In the introduction, I included results from the Yale Program on Climate Change Communication showing that the percentage of American adults who read about climate change in the media at least once a week has ranged between 22 - 33% since 2015. Although major news outlets have increased their climate reporting in the past decade, Nixon says that a central question about the slow violence of climate change is one of representation - how to "convert into image and narrative the disasters that are slow moving and long in the making…disasters that are attritional and of indifferent interest to the sensation-driven technologies of our image-world."

Echoing this climate crisis as a crisis of representation, novelist Amitav Ghosh describes climate change as a "crisis of culture, and thus of the imagination." In "The Great Derangement," he considers why novelists have not seriously engaged the topic of climate change, and why it has been partitioned away into either nonfiction or science fiction genres. As an example, he points to Arundhati Roy, an exquisite novelist whose writings about the environment all show up in her nonfiction writing. Separating the scientific from the literary arts, he suspects, is a result of modern western dualism and the partitioning of nature and culture into separate categories, with culture set hierarchically above nature. We saw this dualism clearly in the quote from congressman Richard Wilde, in chapter two, regarding the passage of the Indian Removal Act. Imploring his fellow congressman to support the act, he asked *"Are our sciences, our arts, our literature, our institutions… to be surrendered to the natural claim of the Indian to the forest?"* This statement echoes both the division between nature and culture and the underlying assumption of superiority. "Natural" claims of the Indians were superseded by the claims of the Western white society Wilde represented. The culture/nature divide also separated reason (which was gendered male) from emotion (which was gendered female), and historian Carolyn Merchant has written extensively about the history of this division in "The Death of Nature: Women, Ecology, and the Scientific Revolution." Merchant documents the historical transition from imagery of earth as a living organism to imagery of earth as machine, coinciding with the scientific and industrial revolutions. This transition to viewing earth as a machine was useful for justifying mining and other forms of resource extraction: "As long as the earth was considered to be alive and sensitive, it could be considered a breach of human ethical behavior to carry out destructive acts against it.[132]"

Now, with mounting evidence for the *geologic* imprint of human activity on the Earth, the partitioning of nature and culture into distinct categories is increasingly tenuous, though still tenacious. Human activity *is* a force of nature. A critical understanding of this dualism and the limitations it imposes on the communication and representation of the climate crisis may help us regard the value of (re-)connecting climate science with the arts and literature.

Music is the medium I chose in this experiment to create artful representations of climate data. The novelty itself, evidenced when listeners exclaim "What?! We can *listen* to climate data?*"* suggests that it awakens fresh new associations to the meaning in the numbers. The neuroscientist Oliver Sacks states so eloquently the capacity of music to express information and emotion at once. In "Musicophilia: Tales of Music and the Brain," he writes, 'The neuroscience of music has concentrated almost exclusively on the neural mechanisms by which we perceive pitch, tonal intervals, melody, rhythm, and so on, and until very recently, has paid little attention to the affective aspects of appreciating music. Yet music calls to both parts of our nature – it is essentially emotional, and it is essentially intellectual." This makes it particularly suitable for conveying climate data with emotional intelligence.

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[132] Merchant, Carolyn, *The Death of Nature: Women, Ecology, and the Scientific Revolution.* Harper Collins, 1980.

In the Spring of 2018, I co-taught a studio course with Dargan Frierson in which students designed and created games, mostly video games, about climate change. The course was designed as a workshop. Students worked in teams on a single prompt over the whole quarter: create a game about climate change that is bound by the science of greenhouse gasses and values equity and human well-being. The student teams determined the rest. Week by week the teams developed various aspects of their games and presented them to other groups for feedback and discussion. We gave mini-lectures about the chemistry and cycling of heat-trapping gasses so that they understood, for example, that carbon dioxide remains in the atmosphere for hundreds of years while other greenhouse gasses, such as methane, have shorter lifetimes in the atmosphere. At the end of the quarter, each team showcased their game, in whatever stage of completion they had reached. For most, it was an early prototype. What stood out to me was an emergent result from the prompt: the games were cooperative. None of the games had individual winners or losers.

One group process, which included students who were majoring in business and economics, was particularly memorable. For this team, the players in the game were individual nations acting in their self-interest and striving to grow their economies. The team did not intend, at the beginning, to create a cooperative game. What they found, through multiple iterations, was that if ‘winning’ meant net zero fossil fuel emissions through pathways that valued equity and human well-being, this could not be achieved by a single country. All nations had to cooperate in order to reach net-zero emissions and stabilize the climate. Global interdependence was an emergent result of their prototyping, under the given constraints.

How is this pertinent to the work of artful data sonification? It’s an example of a way in which open-ended, creative interactions with climate science, for people of various backgrounds, can help them construct their own learning about the range of possible futures that may lie ahead. Taking time to create a game, or to compose or listen to a piece of music about climate data, is a way of making transdisciplinary connections that can spark new ideas and associations through sustained focus.

Distraction and acceleration are hallmarks of our digital culture and fossil fuel economy. The speed and volume at which information crosses our paths everyday make it difficult to sustain our attention on phenomena that have slow and long timescales relative to our digital age. This body of work began with a desire, which grew out of teaching and working with trade unions, to elevate climate data into something people would remember and talk about. It is influenced by many different threads of experience, some of which trace back to earlier periods in my life as I described in the interlude, and others are much shorter but no less prominent. The reactions of listeners are among the short, but prominent threads of influence.

In 2017, I was taking classes in digital sound composition and one of my final projects was a piece about ocean acidification, which layered data sonification with spoken text. In auditioning this piece for the class, one student's reaction was particularly memorable. This student had not appeared to be very engaged in the class, was often looking at his phone and had not offered a comment or asked any questions all quarter. After playing the piece about ocean acidification and inviting feedback, this student raised his hand and said, simply and matter-of-factly: "This made me care more about climate change." I think my jaw may have dropped when he said that. Despite spending most of class time looking at his phone, listening to a composition about ocean acidification drew his attention away long enough to engage with, react to, and comment about climate data. More recently, I attended a music concert dedicated to the global oceans at the National Gallery of Art in Washington DC. My composition *Arctic Sea Ice* was in the program, performed by pianist Anja Arko. In an email exchange leading up to the concert, she told me that her pursuit of environmentally focused music started with listening to *Arctic Sea Ice* in my TED talk. This dissertation, which started as a weekend experiment, grew into a multi-year project because feedback like this suggested that it was helping people find new connections to environmental data.

Climate Data is Not Static

> "I sat down and looked at the music and started singing the melody in my head, like 'where do you want to breathe,' where does this data want to breathe when it is musically expressed?"
>
> \- Kristina Lee

At the end of chapter two, after considering two threads in the history of climate data, I stated that my interest with sonification was in creating a spaciousness around the data so that viewers/listeners might form their own relationship to it. That is what Lee describes here, as she first explored the score to the *Arctic Sea Ice* composition. For her, the data-as-music had a life of its own that she listened for as she began playing the score. The keyboard in this piece represents the satellite sensors which recorded the data. In this way, the musician senses the sea ice cover through their fingertips.

Our relationship to climate data evolves over time. Looking back over the history of the Keeling Curve, Charles Keeling described intense curiosity, in the early stages of monitoring CO_2, that there was a stable background level of CO_2 around the globe, and there was daily cycle: *I soon focused my attention, however, on obtaining more measurements of* CO_2 *in the air because these data showed an intriguing diurnal pattern….theres patterns were similar everywhere I went*. Then, Keeling discovered a seasonal cycle…*We were witnessing for the first time nature's withdrawing* CO_2 *from the air for plant growth during the summer and returning it each succeeding winter.* Now, decades later, we regard this dataset primarily as a reflection of the impact of fossil fuel emissions on the global atmosphere.

In the *Timescales* collection, when we listen to the five year *In Situ* records, we can hear seasonal cycles and a linear trend in the data. As Earth moves along one side of the orbit around the sun, the northern hemisphere tilts toward the light, days grow longer, plants inhale carbon dioxide and get bigger. Then the northern hemisphere tilts away, vegetation dies back, and CO_2 rises a little bit. This cycle repeats. But listening on a different time scale, to *Holocene*, the story is very different. Now, the story in the data is one of unremarkable stability punctuated by a spectacular increase in CO_2 as western Europeans and the United States built a global economy upon fossil fuels. Stepping back further still, to listen to *Glaciations,* the longest record we have, the story now is one of ice ages. Earth's path around the sun is not constant. Small wobbles shift the amount of sunlight impinging on northern hemisphere landmasses and these variations, over hundreds of thousands of years, lead to the growth and melt of ice sheets.

At the time of writing this closing, atmospheric CO_2 reached 423 ppm; a whopping 3 ppm above last year's peak, and a yet another reminder that we live in an age of accelerated change. This acceleration brings long timescales into greater focus for me, because these current levels of atmospheric CO_2 haven't been seen in the geologic record for at least 2 million years. How should we regard the extinctions set in motion by our dependence on ancient sources of fossilized energy?

When I start to become overwhelmed by the near-term data, the hundred-thousand year glacial timescales are a kind of stabilizing salve, a reminder that no species, and no ecosystem lives forever. As one audience member noted, listening to *Glaciations* was "oddly uplifting". Earth has never been ours for the taking, and will long outlive the anthropocene. This grand imperialist experiment of building a world run on fossil fuels is driving up the rate of extinctions, the displacement of human communities, and other changes to Earth of unimaginable magnitude. Those living in the 22nd century will inhabit a world that is staggeringly different from today. Knowing some of the causes and consequences of burning fossil fuels, anticipating more environmental change and loss, and developing a multigenerational temporal perspective may increase our capacity for resilience, repair, and creative change. The experiment I have presented here, of listening to environmental data, is one means of cultivating this kind of knowledge and perspective.

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Appendix I. Unedited Conversation with Kristina Lee and Judy Twedt

December 21, 2018

Judy: Was the piece/process anything like you expected?

Kristina: When Debbie first told me about your work I went to your website and listened to the electronic composition of Arctic Sea Ice (2017), and I thought I was going to play that. When I actually got your score it was completely different than what I expected, and I was delighted.

Judy: When you first started looking at my pieces, had you had much experience looking at climate data or the evidence of climate change?

Kristina: No, not more than an average person, just the news that comes through, but it's not something that I pay a lot of attention to. When I lived in Lebanon, such a small country, they used compostable plastic bags and thought more about sustainability because they are resource poor — even though there is garbage everywhere.
After working with you, I think about small things like reducing waste at the teaching studio when we buy paper cups, and getting my Christmas gifts from the goodwill, and want to contribute, or rather, participate in taking small actions to do my part.

Judy: Why was the piece different than you expected, why were you delighted?

Kristina: Because you use an ancient scale, the pentatonic scale, that is very intuitive to the human experience of music, so it was very relatable to me and I knew it would be relatable to the general audience. And you used the time signature that is also ancient…

Judy: Yeah, when we first met to talk about the score, I think it was in your studio and I was explaining that each chord is one season and each note is one month and we spent a long time thinking about how to explain this clearly to general audiences. Do you remember that process very much?

Kristina: Well you simply explained it to me and it wasn't something that we had to dwell on because it made sense to me right away and when I looked at the music and played the music it was like 'oh yeah, sure this makes perfect sense…'

Judy: …because the musical structure is fairly simple, there's three eighths notes to each left hand chord and those are the seasons

Kristina: Yeah and that BA-da-da, BA-da-da, BA-da-da, that exists in folk music, that experience of rhythm. Everywhere. Celtic music, Asian music, African Music, Native music, the triple notes are closer to the music that's oral tradition than the double music which is European tradition, the BA-ba, BA-ba, BA-ba. I mean you have the polka and stuff but the BA-da-da, BA-da-da, BA-da-da, that was a baroque dance and a Celtic dance. Korean music has that rhythm, you know, so it's interesting to think about the four seasons. The number 12 lends itself to that…

Judy: 12/8 (time signature)

Kristina: Yeah, so it's really interesting to think about your decisions and the decisions that were already made for you, like using the pentatonic scale, and using 12/8, and dividing the seasons. It set up for music that was relatable.

Judy: So in my experience as a translator of data and a composer, a term I'm still trying to identify with, it gave me tingle to see the notes expressed by your hands, because all of my other work was electronic music, but this was seeing human gesture as an interpretation of data, and it was intentional to make the gesture uncomfortable or unnatural as the sea ice melts, and the right hand crosses further and further over the left hand. What did that feel like for you, knowing that you are embodying this transition of sea ice?

Kristina: The first time we went through the whole thing, yeah it gave me goosebumps, just starting to play it, because there's a storytelling before the piece, so I just found that experience to be just very powerful. The combination of the raw data that you thought through and your work of deciding what kind of music to make out of this, and looking at the score, hearing your story, and then playing, it was a really powerful moment. I knew it was gonna work at that point. And, there's an awkwardness to the piece. It's the gestures, you know the reach, but that's in a way not the hardest part because there are overlaps that happen in the first part, because of the seasons and the right hand overlapping with the left hand, but I knew that I needed to bring out the melody which is the data, so there was the awkwardness of trying to execute that within the time, that took some time. How do I make it sound beautiful and haunting while playing every note? Because every note means something here.
So I kept downplaying it like thinking 'oh it's not a really hard piece' because it's not hard like Rachmanninof with lots of notes played fast, but after playing it I decided that it is a 'hard' piece because it is not written with the traditional music composer's approach. So I had to overcome what was given that I could not change.

Judy: Well, and I had to iterate with you, like what's the best way to map this on the score, and your feedback was really helpful in choosing to use the upper staff for the right hand and the lower staff for the left hand, because I made one version of the score that was using traditional notation with the upper staff the treble clef and the lower staff the bass clef and you were like ‘no, this is harder to read!’

Kristina: (Chuckles) yeah, because I had to fish out the melody in the right hand it was like a treasure hunt finding those notes.

Judy: Have you ever seen scores where the right hand and left hand have distinct meanings?

Kristina: I recently played at a Christmas party and played a piece by Philip Glass and chose to do it because it reminded me of your piece.
Going back to playing your music, initially, that initial part when we were trying to figure out the end result — choosing to tie the repeated notes (where the data didn’t change much from month to month – rather than having a separate note on every single beat had a huge impact. We need variation — what pleases people is pattern but it’s boring if you do the same pattern. When you decided to hold the repeated notes, that allowed me to start creating phrases and, you know, once I sat, I got the music and I knew what we were doing, I sat down and looked at the music and started singing the melody in my head, like “where do you want to breathe’, where does this data want to breathe when it is musically expressed.

Judy: That’s such an interesting question and one of the things that makes this really different from writing music and playing music is that, you know, like I basically made a rule, a mapping, and ran the data through that mapping, and I get an output and those are the notes, and I was like ‘here are the notes’ and there was a lot left in terms of the expressivity and phrasing for you to decide, and you did it really beautifully, and those are important questions for the performing artist. You want to express and be true to the data, but there’s still a lot of room for interpretation even staying ‘true to the data’. And that’s one of the exciting things about data sonification. You can make the mapping and then the performer can choose the expressive tone.

Kristina: Yeah, and in this case the composition was 100% your work. In the future this could be more of a collaborative work, I mean, but in this case you made all the right decisions. Like the scales you chose. Scale and time signature, the meter. Those were really really smart choices. A scientist who is less experienced about translating this into music, they may not choose the best scale, or mode, or meter. Those have such an impact. And because you made smart decisions even though the data doesn’t lend itself to musical patterns but I could fish out phrases, and I could rely on them to make musical expressions.

Judy: Was the performance different from performing standard music compositions?

Kristina: There was a pressure because, you know, I wanted to have integrity towards your work and we both wanted to have integrity towards the audience. We, you know, we don’t want to misrepresent the science. At the same time, your speech wasn't about the data, it was how do we have an emotional response and connections to the changes in our environment, so I felt like this needs to, you know, it has to create an emotional response that resonates somehow. So I felt like those two things needed to be delivered, but it was jarring to do this in three and a half minutes. So let me ask you questions. From the time that you started composing music with data, did you envision that there would be a live performer?

Judy: No, all of the pieces I have done until now have been digital, computer-generated music. But I was really excited when TEDx asked me to give a talk and do a live performance. I had been thinking it would be neat to do something with a live performer but I didn't want to collaborate without a commissioned performance, so this made it much more feasible for me. And writing this was a totally different process for me. I totally had this freak-out moment for about two weeks when I thought *I'm not a piano composer, what am I doing, I don't know how to do this, I have not done this before, I've studied digital sound design, not traditional composition.* So I psyched myself out. But then I remembered, I'm not trying to be a traditional music composer, I am turning data into sound. So that really helped me calm down. And there was a moment when I thought, "simple message." Don't make this complicated, so that people can understand the data clearly, or as clearly as possible and just be able to experience it. And I think, you know when I decided to be as literal as possible with the data, to let the keyboard be the y-axis and let the left hand play the zero line on the graph so you can see the data move down the y axis with the right hand. Like, once that thought came to me I was like, "yes this is it, this is what I'm gonna do. I just knew that that was the right thing to do, and I wasn't going to veer off of that structure. And I'm glad I did. The fact that it's both sonic and gestural is so visually compelling to people.

Kristina: So tell me more about that experience, the first few times that I played it, roughly, what was that like, did it change you as a composer?

Judy: Yeah, very much so, and I'm not a traditional music composer. I know many composers can hear melodies in their head before writing them on paper and that's not at all what I did here. I started with the data, and took the data and mapped it to the pentatonic scale, and listened to it as an electronically -generated midi file which sounds nothing like human performance. But I used feedback from listening to the midi files to decide what key and range to use, but I was surprised by how much better and more moving it sounded on a real piano, that was a lovely surprise. I had no idea that I would like it as much as I did.

Kristina: Yeah, it was such a validation of the live performance, in a way, for me as well. We have the you-tube video, it's been recorded more than once now. When we did the rehearsal there was such an emotional reaction too, as a person on the stage, you know, sitting for a while while you talk, then playing. That's a great thing, as a teacher and performer, in this age of technology.

Judy: Right and so much of the reason that there is growing interest in connecting science and the arts is that they're both ways of understanding the world in new ways. Science has very well-practiced empirical methods, and art adds this whole new layer of human meaning and expression. When you combine them, when you understand something scientifically, then bring human expression an art, I think so many people are craving that, especially with climate science and climate data because it does affect us in so many different ways, but when we only have the outlet of talking about the science through graphs and figures we miss being able to slow down and connect to it emotionally, so I think, I was surprised by how, in those early rehearsals with other scientists as the audience, they came up to me afterward and the next day and were like, "your talk is great but we really liked the performance. Like that moved me so much." Because there is a craving for more emotional connections to science, especially for scientists who work with the data day-in and day-out without any emotional outlet…

Kristina: That was so sweet…
So, you met with some people before deciding that you wanted to work with me, and I thought we had a really great working relationship. That was such a pleasant experience to trust each other and give input that was helpful. I mean, I really loved working with you. What do you think is important when you're looking for collaborators?

Judy: I mean, I agree and think we got lucky working together. I think both of us were interested in making it collaborative. I didn't want to just hand you a piece and tell you how to play it, I really wanted feedback, I wanted your input, to make sure it was playable, and to hear a professional performer's perspective. Also, you were really interested in the whole production, the talk, the event itself, so that worked out really well that you were invested in the whole production. And trying something new that neither of us had ever done before, and um, being open to the unknown, and the trial and error.

Kristina: Yeah, and we also had similar value in aesthetics.

Judy: Mm-hmm, kind of minimalist

Kristina: Yeah, we didn't want to over-do it, you know.

Judy: Yeah, and I think we collaborated well because neither of us have big egos.

Kristina: Yea, (both laugh) and we checked in with each other, and also the product, we got a lot of feedback initially, and it wasn't like me just being humble, but we just both agreed that keeping things minimal is the aesthetics that we wanted.

Judy: And I think that choice and aesthetic, when we're talking about Arctic change— the ice-covered arctic ocean is a quiet place and the ice, there's something so elemental about it. Like think about that in contrast to a rainforest where there's a constant cacophony of sounds. I mean, there are sounds in the ocean underneath the ice, but on the sea ice, you know, it occasionally cracks and breaks, and there are wind storms, but the ocean surface is barren, so I think that aesthetic really makes sense for sea ice data.

Appendix II. Outline of Data Sonification Workshop

This is a 2 - 4 hour workshop designed for ages 8 - 18, with at least some background in music notation and familiarity with the piano keyboard. It can be done in 2 hours, but 3 - 4 hours is ideal. Italicized text is a sample script, all other text is information or directions for the facilitator.

Participant Learning Goals:

- Compose music with data by mapping data to piano notes
- Describe how their mapping choices affect the sound of the music
- Understand the variable effects of climate change, by hearing how different cities around the world are warming at different rates

Materials:

Print-outs of city temperature data

Copies of a piano keyboard for everyone

Paper and pencils

White board

Access to keyboards for the participants (or iPads with keyboards could also work)

Outline

Icebreaker

Help us guess what city you were born in, without telling us the name of the city

Part 1: Making connections between numbers, data, and notes

Before we look at the climate data from cities, I want us to think a little bit about data and numbers.

When we collect data, we start with things we can touch or feel, see and count them.

For many people our earliest experience with data is when we learn to count.

Often we learn to count using our fingers — something we can touch, feel, and see, and turn it into numbers — 1,2,3,4,5.

This is how we take data.

Data is another way to go from something real that we can see or feel to something abstract. We can feel temperature, and we measure it and represent it with numbers.

For example (write this on a white board or other visible space):

[1, 1, 5, 5, 6, 6, 5, 4, 4, 3, 3, 2, 2, 1]

Break-out: map numbers to notes

Using the keyboard hand-out, participants make a piece from the set of numbers (above). Assign a different tonic to each student, only using white keys. Students choose the rhythm.

The goal of this activity is for students to learn that a set of numbers can be expressed musically in many different ways, depending on how you map it to the keyboard, and what rhythm you choose.

Part 2: Sonify Temperature Data, step 1

Pass out SeaTac weather station data showing how hot it gets each day. Look at **yearly and decadal** values. Explain that this data is taken from a weather station that measures temperature throughout the day. When we take an average over a long time period, like a year, it allows us to see how it's changing from year to year without having to look at so many numbers.

Discussion questions:

What do we notice about the yearly and decadal data?

What can we learn from these averages?

Maybe we can learn something about this from turning it into music!

Break-out: sonify the Sea-Tac decadal station data

Tell participants to choose their staring note and use the following rule:

1 degree Fahrenheit = 1 degree on your scale (or one white note on the keyboard)

Regroup, listen to each-other's pieces. Discuss variations such as playing each note slowly, adding harmony, choosing different scales.

[break]

Mini lesson: Sonify Temperature Data, step 2

Now we're going to compose with climate data. Music is one way to help people pay attention and to think about science in a new way.

When we make music from climate data, we get to make choices about how the data will *sound— it could sound slow and calm, slow and sad, quick and exciting, or loud and scary. You can ask yourself what the data is saying and how you feel about that, before you decide how to turn it into music.*

Discussion: *Why do we need data to understand climate change?*

Choices for sonification:

- Choose your city (data)
- Choose your starting note
- Choose the mapping (one degrees in the scale = X degrees F)
- Write your notes next to your numbers
- Set your tempo
- Add harmony, or a longer/shorter time series to play at the same time (i.e. you could play both annual and decadal temperature values)

The facilitator models how to make each of these choices, and encourages participants to experiment and play with different choices!

Break-out: **sonify temperature data of choice**

Participants make a composition from city data of choice, following the guidelines above

Regroup for feedback, share progress, ask questions

Break-out: **continue sonification**

Take an additional 15 - 20 minutes to either continue working on piece, or sonify a different city.

Last 20-30 minutes: Share sonifications!

Appendix III. Datasets for Breathing in a Time of Disaster

Dataset	Format	Notes
Interview with Becky Alexander	Audio wav file	Recording date: 5/11/2019
Interview with Angelique Demetillo	Audio wav file	Recoding date: 9/26/2022
Interview with Emily Pinckney	Audio wav file	Recording date: 10/6/2022
Interview with Mariel Thuraisingham	Audio wav file	Recording date: 10/24/2022
Interview with Debolina Banerjee	Audio wav file	Recording date: 10/20/2022
Seattle breath recordings	Audio wav files	Recorded at Jack Straw Cultural Center
Houston breath recordings	Audio wav files	Recorded by participants
Air quality data, Seattle	By FIPS code (census tract)	Washington Tracking Networks Environmental Public Health Data, *Diesel Pollution and Disproportionate Impact* index
Air quality data, Houston	By census tract, data was processed to compute zip code averages	Demetillo, M. A. G., Navarro, A., Knowles, K. K., Fields, K. P., Geddes, J. A., Nowlan, C. R., Sun, K., Judd, L. M., Al-Saadi, J., Diskin, G. S., McDonald, B. C., and Pusede, S. E.: Observing nitrogen dioxide air pollution inequality using high-resolution remote sensing measurement in Houston, Texas, *Environ. Sci. Technol.*, doi:10.1021/acs.est.0c01864, 2020.
Life expectancy data, Seattle	By census tract, data was processed to compute zip code averages	Washington Tracking Networks Environmental Public Health Data, from 2010-2016 average

Life expectancy data, Houston	By zip code	https://www.texashealthmaps.com/lfex, accessed 11/10/22

Appendix IV. Undergraduate Student Responses

Student feedback from a presentation I gave for a seminar class that surveyed different topics in atmospheric sciences. Each week students heard from a different scientist working in atmospheric sciences. In week 8, I presented on the timescale of climate change using the sonification of the Keeling Curve and the Arctic Sea Ice. At the end of the quarter, students submitted a course survey.

This feedback was a response to the question *What stretched your thinking the most?* A total of 142 students answered this quest, and 39 wrote specifically about the lecture with data sonification, which occurred in week 8.

Climate music: I have heard some natural events put to music but never on a data-based 'scale' of decades to millennium. very nice!

Judy Twedt's lecture about climate music stretched my thinking the most. In the past, I didn't care about climate change at all except the temperatures every day. After hearing the presentation, I learned that lots of things will affect the climate. For example, fossil fuels can make a heat-trapping blanket in the atmosphere, producing air pollution. I also noticed great changes in the earth's temperature over the past 60 million years. We should care more about climate changes in the future in order to protect the earth.

I liked hearing about a more philosophical view of climate science. I think about implications and ethics related to global warming a lot, and it was a nice change of pace. It also seemed to stand alone in terms of jobs/opportunities for climate scientists. I appreciated the translation of climate records to music, and I think that makes a relatable message for people.

Judy Twedt's presentation was the most interesting as someone in the atmospheric science major. I had never seen climate presented in any way other than math and physics! When her talk first started, honestly I thought representing the climate with sound seemed a bit strange. It wasn't until the middle/end when she played the piano piece that represented the loss of ice in the Arctic, that I realized how useful her work could be in informing the public about climate change. It was very alarming.

Judy Twedt's presentation raised an important point: how do you present the ideas of something as monumental as climate change to people with diverse opinions and ethics? I never would *have thought to present scientific data using art forms, such as music or poems. I learned the best way to communicate ideas in such a sensitive topic would be to present the ideas in a less partisan manner. Using numerical data and facts to address an issue as well as attack a person's opinion and expertise is not productive in an age where scientific data and "facts" are subject to increased scrutiny. Art forms are a good solution to this, making scientific data and observations more relatable.*

week 8's lecture stretched my thinking the most because it provides a different perspective for us to look at climate. I have never thought about the climate changes that can be displayed by music and it is really interesting. Also, different scales allow us to see more differences in climate.

I believe that Judy Twedt stretches my thinking a lot with climate music. Her desire to bring music together with the climate was very random to me but made me realize that you can do anything your heart desires. It was really amazing to hear all the different sounds that was created. The piano piece was also very inspirational to me, as someone who admires musicians, to see it combined with climate change, it was amazing!

I like Judy's lecture about climate music because it offers a different perspective for people to think about climates. I am a musician and an artist, which is also why I found such particular connections to her lecture.

Judy Twedt's climate music was one of my favorite lectures that not only stretched my thinking on climate change but on atmospheric studies as a whole. I did not know that media and atmospheric studies could be put in a mashup in hopes of educating others on the topic of climate change. The music of increased greenhouse gasses really puts the topic of climate change into perspective. How compressing time can really change perspective of change. From our 'live in the moment' mindset, it's easy to deny climate change as an issue because everyone is seemingly living well, however, with the music she created, it comes to show just how big an issue climate change is, and how quickly it is escalating.

I thought Judy Twedt's lecture on climate was the coolest. It really helped us visualize the data trends of the past decade through the medium of music. It had much more impact on me than just a graph and got me thinking more so than other presenters. The data visualization through auditory simulation was really really interesting.

Judy Twedt's lecture about climate music stretched my thinking the most. The incorporation of data into music is not something I had every thought of before. The fact that there are other avenues and mediums to share data was eye-opening. It was also neat seeing someone combine their two passions and be able to share what they learned in a way that would engage multiple audiences.

I really enjoyed Judy Twedt's lecture on climate music. It was interesting to see climate change and CO2 emissions turned into a midi file and then a song. I remember hearing that type of thing when I took ATMS 111 last year and it was a good reminder of that. The music was a good representation of climate change and not only the rising temperature but also the fluctuation each year. I liked the hip hop beat they added too.

I would say week 8 stretched my thinking the most because it was something I had never considered before. Representing data with music seemed strange to me at first but after listening to her talk and explain it I began to understand how it was a new and valuable way to experience data. Music is also something I am passionate about so it is cool to see my love of science and music united.

Before Judy's lecture, I hadn't really thought about the intersection of atmospheric sciences and humanities. The concept of music influencing emotions was powerful. I was quite surprised by the idea of using music to influence how people think and feel about climate change. My thinking was also stretched by considering how I felt about climate change both before, and after the presentation.

I think it is the lecture on week 8 that stretched my thing most. I never think that music can become a way to represent climate change and this representation really does make the change more impressive to me. It is also very interesting to compare climate change within a longer period of time and within a shorter period. Note that even there is no sign for huge climate change in less than 3 months, after we zoom out, there might be a huge change in a long period.

Ahh that's a hard choice to make. They were all so interesting and had such different focuses. I guess I find the topic of science communication generally compelling. I'm always put off by online articles with clickbait titles about the newest diet advice or top home remedies based on some questionable study, as well as misleading paraphrases of a sound study. Unfortunately, much of the public relies on these secondary sources because science journals aren't that accessible.That's why the work Judy Twedt does is super amazing, A) I didn't know that a career like hers even existed, B) her climate music is really engaging and reaches a broader audience who might not be interested otherwise, and C) represents important data in a way that is easy to understand. Her other campaigns are also very effective. The video that she made on how to talk about climate change shows that facts aren't enough to get the message across. It's essential to be approachable and relatable. This is especially applicable when trying to create climate change policy, something America is currently struggling to do >:[

From the last five lectures, I found Judy's lecture on climate music stretching my thinking the most. Firstly, It totally caught my attention when I heard the poem about the origin of the *universe. It changed my mind of considering ATM S to be purely mathematical computation and scientific analysis while the beauty of literature about ATM S made me interested in exploring more about it. Then the music made by climate data blew up my mind again since it changed from visual analysis to another direct auditory sense. From music, it is a more direct sense of whether there is an increasing trend or a randomized fluctuation in the data set. This strategy taught me another way of looking at the data from all other different experiments.*

The lecture which stretched my thinking the most was the one from Week 8 involving the climate music. It provided another perspective on looking at climate change models and trends we see in weather, and more importantly, CO2 levels in the atmosphere. The use of sounds provides a different medium of understanding relative importance of climate change problems because of how it changes our view of time as a scale. I also thought that it was a really interesting way of representing data, through music, because it is a medium not seen as often in science research.

Week 8: Judy Twedt, climate music was the most interesting and intellectually stimulating lecture for me in various ways. First of all, we listened to a musical piece, which was a sonic and gestural interpretation of the satellite record of arctic sea ice. This was fascinating because since I play piano too, it was so interesting to hear what had been happening to the arctic sea ice in a musical interpretation. The melting of the Arctic Sea ice was due to increasing temperature from heat trapped in the atmosphere. Various natural and human-activity that cause an increase in carbon dioxide level in the atmosphere lead to increasing temperature. In addition, the formation of heat-trapping blanket in the atmosphere due to fossil fuels were worsening the situation of the global climate change. Not only learning about the facts in class, but listening to the interpretation of data had helped me stretch my intellectual curiosity for the global climate change.

Judy Twedt stretched my thinking the most because she presented the information in a musical and art form. The way she represented the climate models and projections over time really made me grasp how quickly the climate is changing because I could hear it. Her presentation was unlike anything I have ever seen about climate change or atmospheric science. It was a very interesting lecture.

Week 8 on climate music. It's the most interesting one because it combines climate change to music. So that it really enhances our understanding on climate change without being boring. Amazing lecture!

I liked Judy's talk very much. It was a very impressive lecture on the concept of climate change. With the music of greenhouse gases concentration and the glacier area changes, I learned how much our climate has changed in a short amount of time. I was only told that climate change is happening and it is severe but I have never had such an impressive concept of how much it is.

I liked Judy Twedt because it gave me a concrete idea of exactly how rapidly and consistently the climate is changing

Personally, I thought that Judy Twedt's idea stretched my thinking the most. As a musician, I never had thought about that application of using music to model what was happening with climate. It made me think about not only what else could be modeled with music in the future, but how obvious music demonstrated the idea she was getting across, rather than seeing more graphs explaining things I already knew. This stretched my thinking because it got me curious about what else within Atmospheric Science could be modeled using music and how the style of the composer can very drastically change the meaning a piece could have based on their decisions for tone, tempo, and the issue they were addressing.

I was surprised a lot by Week 8 about climate music. It was surprising for me and it's amazing. I never believed things about that until I heard that.

Judy Twedt definitely. Her choice of topic is by far the most interesting one I have learned regarding climate change. Her presentation showed me that concrete data and numbers aren't what is needed to raise awareness for climate change. It was a very unique and powerful message she conveyed through her presentation. It was very thoughtful of her to incorporate music and the alarming climate change. Her presentation is without a doubt the most unique and powerful one I've listened to.

I believe week 8 with Judy stretched my thinking the most because I never realized that you could utilize music to define climate change over long periods of time. I understand how hard it is to rationalize long periods of time since you can't sense it as easily as an hour or a day. I also believe that climate change is a problem that needs to be rectified in the coming years. Her music could help guide others into understanding climate change as a whole.

Week 8's climate music stretched my thinking the most. This really affected my opinion on just how huge climate change really is and what the future holds. Particularly how if we look at things at a smaller time period, there may be some changes but the more important patterns occur when we take a step back and look at things at a larger time period. Through this, we saw just how much CO_2 concentrations have been increasing for the past century and in particular the more recent decades.

Judy Twedt's lecture was very different from all the rest. Though many of the lecturers have made their own niche in the world combining atmospheric science with other fields, none have done so quite as creatively or differently from the rest as Judy. Her passion for her work and for the *world are truly mind opening and I think she is onto something that could be absolutely world changing.*

Week8. Climate music is very interesting because climate change is around our daily life. We face the different climate every day and learn how to differentiate climate is important for us.

The lecture on climate music definitely stretched my thinking the most. I was very skeptical at the beginning of the lecture about whether this work was even worthwhile, but by the end I realized that being able to hear the difference in climate data was very impactful. I even shared the piano piece on Facebook after class! For those who may be unable to understand graphs and tables of data, I now think that audibly being able to hear a change is a pretty cool way of getting a point across.

It's a really interesting topic. I got to know more about this world. I gained more knowledge about climate. I understood the changes in climate.

The presentation Judy Twedt gave was the most impressive one for me. She introduced climate in a musical way which was very neoteric. It is also very simple to understand how temperature changes through so many years. Moreover, it is easier to remember the music than remembering data.

Out of the last 5 lectures, Judy Twedt's lecture on climate music stressed my thinking the most. I had never previously thought of climate in the context of music or anything art-related. Listening to her various audio clips made me think about climate change in another way. I particularly enjoyed the piano rendition that represented the change in temperature over many years. The lecture was unique and I appreciated the alternative perspective.

Judy Twedt's lecture gave me the deepest impression. Because using music to describe climate is a totally new way to me and it is so interesting. It makes me wanna know more about music expression about climate. And I think it helps people get close to climate change.

Week 8 because it was so interesting to see graphs shown as music. I never thought of presenting data as music and it does make things more noticeable. It's easier to care and notice change as sound whereas in a graph, someone without a math background may not know how to read a graph and interpret it.

Judy Twedt's lecture on climate music stretched my thinking the most out of the last five lectures. At the beginning of the lecture, to say I was skeptical of her work, would be an understatement. After listening to the recordings that she created, I realized how tremendously helpful her studies and creations are to understanding climate. Not to mention, they were incredibly interesting.

I really enjoyed Judy Twedt's climate music. I never considered this way of bridging arts and connecting people to the more factual parts of science and it makes me consider the ways that I can interpret information or advancements in technology and the ways of framing it so that people who aren't experts are still able to connect and understand with the information I'm dealing with. It was also just incredibly engaging. I liked the different ways of interaction she provided her audience during her presentation. Overall, it was just enjoyable and interesting.

Appendix V. Museo do Mar Exhibition Announcement

This exhibition included the music video *The Deafening Rise of Carbon Pollution,* translated into Portuguese. This sonification is described in chapter four.

ALTERAÇÕES CLIMÁTICAS E OS OCEANOS DO FUTURO

MUSEU DO MAR REI D. CARLOS

10 FEVEREIRO A 31 JULHO '19

As alterações climáticas fazem parte da história geológica da Terra. Contudo, desde a Revolução Industrial, o uso crescente de combustíveis fósseis, os processos industriais e as alterações no uso do solo (por exemplo, desflorestação) têm contribuído para o aumento da concentração de gases com efeito estufa na atmosfera e, assim, acelerado o ritmo das alterações climáticas. O aumento da concentração destes gases, em especial de dióxido de carbono, resultou até hoje numa tendência de aquecimento, acidificação e, consequentemente, de redução dos níveis de oxigénio dos oceanos. Por sua vez, estas alterações no ambiente marinho têm originado perdas significativas de biodiversidade, mudanças na distribuição geográfica de diversas espécies, e uma diminuição na resiliência dos ecossistemas marinhos, com profundos impactos não só a nível ambiental, mas também económico, social e político.

A consciência da sociedade relativamente aos impactos das alterações climáticas na vida quotidiana é, no entanto, ainda bastante limitada. Sensibilizar os cidadãos para esta problemática é de extrema importância, em especial num contexto de proximidade à zona costeira, onde a dependência de recursos marinhos (por exemplo, atividade piscatória) torna as populações humanas particularmente vulneráveis aos impactos das alterações climáticas no oceano. O MARE-Faculdade de Ciências da Universidade de Lisboa, centro de excelência na investigação sobre os efeitos das alterações climáticas nos ecossistemas marinhos, juntamente com o Museu do Mar Rei D. Carlos, pretendem contribuir através da presente exposição, para o aumento da literacia dos oceanos, bem como para uma maior conscientização relativa aos impactos das alterações climáticas nos bens e serviços do oceano.

CLIMATE CHANGE AND THE OCEANS OF TOMORROW

KING D. CARLOS SEA MUSEUM

FEBRUARY 10 to JULY 31 '19

Climate changes are part of Earth's geological history. However, since the Industrial Revolution, the increasing use of fossil fuels, industrial processes and land-use changes (e.g. deforestation) have contributed to the increased concentration of greenhouse gases in the atmosphere and thus, accelerated the pace of climate change. The increase in the concentration of these gases, in particular carbon dioxide, has resulted to date in a warming trend, acidification and therefore reduction of oxygen levels in the oceans. In turn, these changes in the marine environment have resulted in significant losses of biodiversity, changes in the geographical distribution of species, and a decrease in the resilience of marine ecosystems, with profound impacts not only on the environmental level, but on the economic, social and political also.

Society's consciousness in relation to the impacts of climate change in everyday life is, however, still quite limited. Raising public awareness to this problem is extremely important, particularly in relation to coastal communities, where dependence on marine resources (e.g., fishing activity) makes human populations particularly vulnerable to the impacts of climate change in the ocean. The MARE-ULisboa (Marine and Environmental Sciences Centre-University of Lisbon), research centre of excellence on the effects of climate change on marine ecosystems, together with the King D. Carlos Sea Museum, intend to contribute with this exhibition towards an increase in ocean literacy as well as raise awareness about the impacts of climate change on the Ocean's resources and services.