Earth System Music: music generated from the United Kingdom Earth System Model (UKESM1)

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Abstract.

Scientific data are almost always represented graphically in figures or in videos. With the ever-growing interest from the general public towards understanding climate sciences, it is becoming increasingly important that scientists present this information in ways that are both accessible and engaging to non-experts.

In this pilot study, we use time series data from the first United Kingdom Earth System model (UKESM1) to create six procedurally generated musical pieces. Each of these pieces presents a unique aspect of the ocean component of the UKESM1, either in terms of a scientific principle or a practical aspect of modelling. In addition, each piece is arranged using a different musical progression, style and tempo.

These pieces were created in the Musical Instrument Digital Interface (MIDI) format and then performed by a digital piano synthesizer. An associated video showing the time development of the data in time with the music was also created. The music and video were published on the lead author's YouTube channel. A brief description of the methodology was also posted alongside the video. We also discuss the limitations of this pilot study, and describe several approaches to extend and expand upon this work.

1 Introduction

The use of non-speech audio to convey information is known as sonification. One of the earliest and perhaps the most well known applications of sonification in science is the Geiger counter; a device which produces a distinctive clicking sound when it interacts with ionising radiation (Rutherford and Royds, 1908). Beyond the Geiger counter, sonification is also widely used in monitoring instrumentation. Sonification is appropriate when the information being displayed changes in time, includes warnings, or calls for immediate action. Sonification instrumentation is used in environments where the operator is unable to use a visual display, for instance if the visual system is busy with another task, overtaxed, or when factors such as smoke, light, or line of sight impact the operators visual system (Walker and Nees, 2011). Sonification also allows several metrics to be displayed simultaneously using variations in pitch, timbre, volume and period (Pollack and Ficks, 1954; Flowers, 2005). For these reasons, sonification is widely used in medicine for monitoring crucial metrics of patient health (Craven and Mcindoe, 1999; Morris and Mohacsi, 2005; Sanderson et al., 2009).

Outside of sonification for monitoring purposes, sonification of data can also be used to produce music. There have been several examples of sonification of climate system data. *Climate symphony* by Disobedient films, (Borromeo et al., 2016) is a musical composition performed by strings and piano using observational data from sea ice indices, surface temperature and carbon dioxide concentration. Daniel Crawford's *Planetary Bands, Warming World*, (Crawford, 2013) is a string quartet which uses observational data from the Northern Hemisphere temperatures. In this piece, each of the four stringed parts represents a different latitude band of the Northern Hemisphere temperature over the time range 1880-2012. Similarly, the climate music project, https://climatemusic.org/, is a project which makes original music inspired by climate science. They have produced three pieces which cover a wide range of climatological and demographic data and both observational and simulated data. However, pieces like (Borromeo et al., 2016) and (Crawford, 2013) often use similar observational temperature and carbon dioxide datasets. Both of these datasets only have monthly data and approximately one century of data or less available. In addition, both temperature and carbon dioxide have risen since the start of the observational record. This means that these musical pieces tend to have similar structures and sounds. The pieces start slowly, quietly and low pitched at the start of the dataset, then slowly increase, building up to a high pitch conclusion at the present day. It should be noted that all the pieces list here are also accompanied by a video which can explain the methodology behind the creation of the music, shows the performance by the artists, or shows the data development while the music is played.

An alternative strategy was deployed in the Sounding Coastal Change project (Revill, 2018). In that work, sound works, music recordings, photography and film produced through the project were geotagged and shared on to a sound map. This created both a record of the changing social and environmental soundscape of North Norfolk. They used these sounds to create music and explore the ways in which the coast was changing and how people's lives were changing with it.

In addition to its practical applications, sonification is a unique field where scientific and artistic purposes may coexist (Tsuchiya et al., 2015). This is especially true when in addition to being converted into sound, the data are also converted into music. This branch of sonification is called musification. Note that the philosophical distinction between sound and music is beyond the scope of this work. Through the choice of musical scales and chords, tempo, timbre and volume dynamics, the composer can attempt to add emotive meaning to the piece. As such, unlike sonification, musification should be treated as a potentially biased-interpretation of the underlying data. It can not be both musical and a true objective representation of the data. Furthermore, even though the composer may have made musical and artistic decisions to link the behaviour of the data with a specific emotional response, it may not necessarily be interpreted in the same way by the listener.

With the ever-growing interest from the general public towards understanding climate science, it is becoming increasingly important that we present our model results and methods in ways that are accessible and engaging to non-experts. In this work, six musical pieces were procedurally generated using output from a climate model; specifically, the first version of the United Kingdom Earth System Model (UKESM1) (Sellar et al., 2019). By using simulated data instead of observational data, we can generate music from time periods outside the recent past such as the pre-industrial period before 1850 and multiple projections of possible future climates. Similarly, model data allows access to regions and measurements far beyond what can be found in the observational record. The UKESM1 is a current generation computational simulation of the Earth's climate and has been deployed to understand the historical behaviour of the climate system as well as make projections of the climate in the future. The UKESM1 is described in more detail in sec. 2. The methodology used to produce the pieces and a brief summary of each piece is shown in sec. 3. The aims of the project are outlined below in sect. 4.

Each of the six musical pieces was produced alongside a video showing the time series data developing concurrently with the music. These videos were published on the YouTube video hosting service. This work was an early pilot study and has revealed several limitations which we outline in sect. 5. We also include some possible extensions, improvements and new directions for future versions of the work.

2 UKESM1

The UKESM1 is a computational simulation of the Earth System produced by a collaboration between the Hadley Centre Met Office from the United Kingdom and the Natural Environment Research Council (NERC) (Sellar et al., 2019). The UKESM1 represents a major advance in Earth System modelling, including a new atmospheric circulation model with a well-resolved stratosphere; terrestrial biogeochemistry with coupled carbon and nitrogen cycles and enhanced land management; troposphere-stratospheric chemistry allowing the simulation of radiative forcing from ozone, methane and nitrous oxide; a fully featured aerosol model; and an ocean biogeochemistry model with two-way coupling to the carbon cycle and atmospheric aerosols. The complexity of coupling between the ocean, land and atmosphere physical climate and biogeochemical cycles in UKESM1 is unprecedented for an Earth System model.

In this work, we have exclusively used data from the ocean component of the UKESM1. The UKESM1's ocean is subdivided into three component models: the Nucleus for European Modelling of the Ocean (NEMO) simulates the ocean circulation and thermodynamics (Storkey et al., 2018), the Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification (MEDUSA) is the sub model of the marine biogeochemistry (Yool et al., 2013) and CICE simulates the growth, melt and movement of sea ice (Ridley et al., 2018).

The UKESM1 is being used in the UK's contribution to the sixth international coupled model intercomparison project (CMIP6) (Eyring et al., 2016). The UKESM1 simulations that were submitted to the CMIP6 were used to generate the musical pieces. These simulations include the pre-industrial control (pi-Control), several historical simulations and many projections of future climate scenarios. The CMIP6 experiments that were used in these works are listed in tab. 1.

This is not the first time that the UKESM1 has been used to inspire creative projects. In 2017, the UKESM1 participated in a science and poetry project where a scientist and a writer were paired together to produce poetry. Ben Smith was paired with L. de Mora and produced several poems inspired by the United Kingdom Earth System Model (Smith, 2018).

3 Methods

In this section, we describe the method used to produce the music and the videos. Figure 1 illustrates this process. The initial data are UKESM1 model output files, downloaded directly from the United Kingdom's Met Office's data storage system, MASS. These native-format UKESM1 data will not be available outside the UKESM collaboration, but selected model variables have been transformed into a standard format and made available on the Earth System Grid Federation via, for example, https://esgf-index1.ceda.ac.uk/search/cmip6-ceda/.

The time series data are calculated from the UKESM1 data by the BGC-val model evaluation suite (de Mora et al., 2018). BGC-val is a software toolkit that was deployed to evaluate the development and performance of the ocean component of the UKESM1. In all six pieces, we use annual average data as the time series data. The datasets that were used in this work are listed in tab. 1.

Each time series dataset is used to create an individual Musical Instrument Digital Interface (MIDI) track composed of a series of MIDI notes. The MIDI protocol is a standardised digital way to convey musical performance information. It can be thought of as instructions that tell a music synthesizer how to perform a piece of music (The MIDI Manufacturers Association, 1996). All six pieces shown here are saved as a single MIDI file, which contains one or many MIDI tracks played simultaneously. Each MIDI track is composed of a series of MIDI notes.

Each MIDI note is assigned four parameters. The first two parameters are timing: when the note occurs in the song, and duration: the length of time that the note is held. The timing is the number of beats between this note and the beginning of the song. The duration is positive rational number representing the number of beats for the note to be held. A unity duration is equivalent to a crotchet (quarter note), a duration of two is a minim (half note), a duration value of a half is a quaver (eighth note).

The third MIDI note parameter is the pitch, which in MIDI must be an integer between 1 and 127, where 1 is a very low pitch and 127 is a very high pitch. These integer values represent the chromatic scale and middle-C is set to a value of 60. The pitch of the MIDI notes must be an integer, as there is no capability in MIDI for notes to sit between values on the chromatic scale. Musically, this can be explained that there are not notes in-between the notes on a keyboard in MIDI. The total range of available pitches covers ten and a half octaves, however we found that pitches below 30 or above 110 started to become unpleasant when performed by TiMidity; other MIDI pianos may have more success. Also note that MIDI's 127 note system

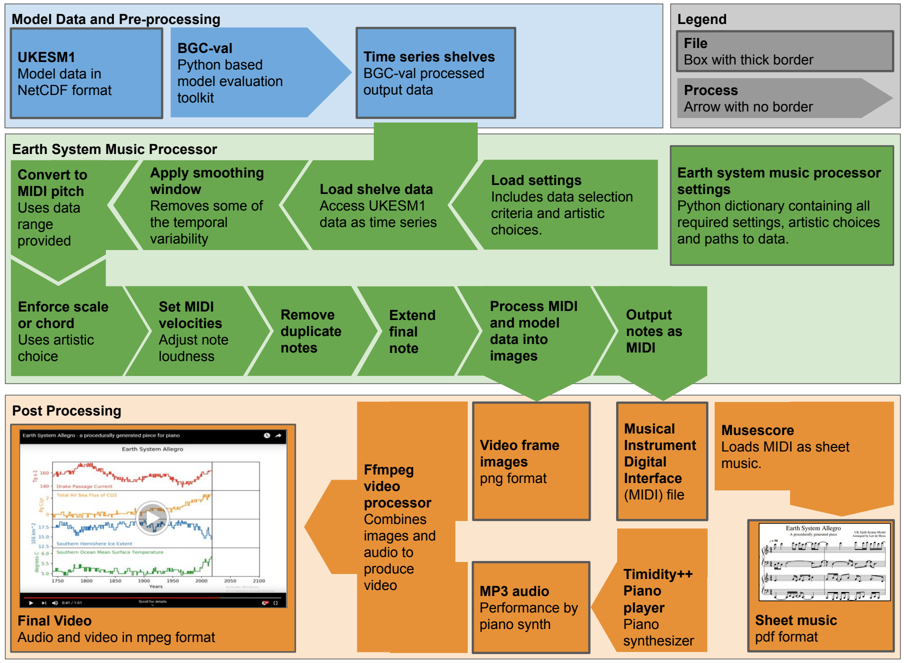

Figure 1. The computational process used to convert UKESM1 data into a musical piece and associated video. The boxes with a dark border represent files and datasets, and the arrows and chevrons represent processes. The blue areas are UKESM1 data and the pre-processes stages, the green areas show the data and processing stages needed to convert model data into music in the MIDI format, and the orange area shows the post processes stages which convert images and MIDI into sheet music and videos.

extends beyond the standard piano keyboard which only covers the range 21-108 of the MIDI pitch system. MIDI uses the twelve tone equal temperament tuning system - while this is not the only tuning system, it is the most widely used in Western music.

The fourth MIDI note parameter is the velocity; this indicates the speed with which the key would be struck on a piano and is the relative loudness of the note. In practical terms, velocity is an integer ranged between 1 and 127 where 1 is very quiet and 127 is very loud. The overall tempo of the piece is assigned as a global parameter of the MIDI file in units of the number of beats per minute.

Each model time-series dataset is converted into a series of consecutive MIDI notes, which together form a track. For instance, the Sea Surface Temperature (SST) time series could be converted into a series of MIDI notes in the upper range of the keyboard, forming a track. For each track, the time series data are converted into musical notes such that the lowest value in the dataset is represented by the lowest note pitch available, and the highest value of the dataset is represented by the highest pitch note available. The notes in between are assigned proportionally by their data value between the lowest and highest pitched notes. The lowest and highest notes available for each track are pre-defined in the piece's settings and they are considered an artistic decision. Each track is given its own customised pitch range, so that the tracks may be lower pitch, higher

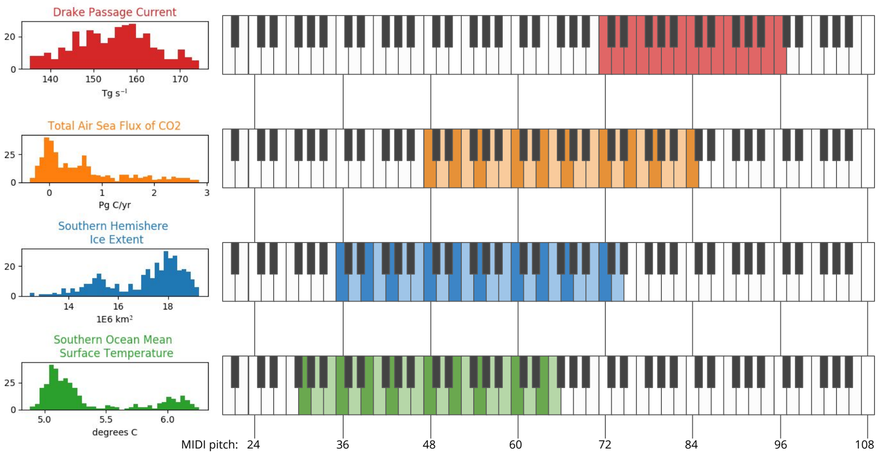

Figure 2. The musical range of each of the datasets used in the *Earth System Allegro*. The four histograms on the left hand side show the distributions of data used in the piece, and the right hand side shows a standard piano keyboard which the musical range available to each dataset. In this piece, the Drake Passage current, shown in red, is free to vary within a two octave range of the C major scale. The other three datasets have their own ranges, but are limited to the notes in the chord progression C major, G major, A minor F major. The dark coloured keys are the notes in C major chord, but the lighter coloured keys show the other notes which are available for the other chords in the progression. Note that both the C major scale and chord do not include any of the ebony keys on a piano, but these notes could be used if they were within the available range and appeared in the chord progression used.

pitch or have overlapping pitch ranges relative to other tracks in the piece. The ranges of notes available for the piece *Earth System Allegro* is shown in fig. 2. In this figure, the four histograms on the left hand side show the distributions of data used in the piece, and the right hand side include four standard piano keyboards showing the musical range available to each dataset. For instance, the Drake Passage Current ranges between 135 and 175 Tg s^{-1} in these simulations and we selected a range between MIDI pitches 72 and 96. This means that the lowest Drake Passage current values (135 Tg s^{-1}) would be represented in MIDI with a pitch of 72 and the highest Drake Passage current values (175 Tg s^{-1}) would be assigned a MIDI pitch of 96, which is two octaves higher.

These note pitches are then binned into a scale or a chord. The choice of chord or scale depends on the artistic decisions made by the composer. For instance, the C major chord is composed of the notes C, E and G, which are the 0^{th}, 4^{th} and 7^{th} notes respectively in the 12 note chromatic scale starting from C at zero. Figure 3 shows a representation of these notes on a standard piano keyboard. The C major in the zeroth octave is composed of the following set of MIDI pitch integers:

$$C_{maj_0} = \{0, 4, 7\} \quad (1)$$

In the twelve tone equal temperament tuning system, the twelve named notes are repeated and each distance of 12 notes represents an octave. As shown in fig. 3, a chord may also include notes from subsequent octaves. In this figure, the C major

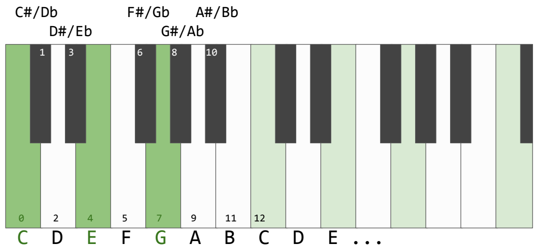

Figure 3. A depiction of a standard piano keyboard, showing the names of the notes, the number of these notes in MIDI format. The C major chord is highlighted in green, and the zeroth octave is shown in a darker green than the subsequent octaves.

chord is highlighted in green, and the zeroth octave is shown in a darker green than the subsequent octaves. As such, the C major chord can be formed from any of the following set of MIDI pitches:

$$C_{maj_{0,1,2...}} = \{0, 4, 7, 12, 16, 19, 24, 28, 31 \dots 127\} \quad (2)$$

It then follows that the notes of the C major chord are values between 0 an 127 where the condition is true:

$$p \in C_{maj_{0,1,2...}}$$

This can be can be written more simply as:

$$p \,\%\, 12 \in C_{maj_0}$$

where p represents the pitch value: an integer between the minimum and maximum pitches provided in the settings, and the percent sign (%) represents the remainder operator.

The zeroth octave values for other chords and scales with the same root note can be calculated from their chromatic relation with the root note. For instance:

$$C_{min_0} = \{0, 3, 7\}$$

$$C^7_{maj_0} = \{0, 4, 7, 11\}$$

$$C^7_{min_0} = \{0, 3, 7, 10\}$$

$$\dots$$

Note that the derivation of these chords and their nomenclature is beyond the scope of this work. For more information on music theory, please consult an introductory guide to music theory such as Schroeder (2002) or Clendinning and Marvin (2016).

The zeroth octave values for other keys can be included by appending the root note of the scale ($C:0$, $C\#/Db:1$, $D:2$, $D\#/Eb:3$ and so on) to the relationships in the key of C above. For instance,

$C_{maj_0} = \{0,4,7\}$

$C\#_{maj_0} = \{0,4,7\}+1 = \{1,5,8\}$

$D_{maj_0} = \{0,4,7\}+2 = \{2,6,9\}$

$D\#_{maj_0} = \{0,4,7\}+3 = \{3,7,10\}$

$\ldots$

Using these methods, we can combinatorially create a list of all the MIDI pitches in the zeroth octave for all 12 keys for most standard musical chords. From this list, we can convert model data into nearly any choice of chord or scale.

The conversion from model data to musical pitch is performed using the following method. First, the data are translated into the pitch scale, but kept as a rational number between the minimum and maximum pitch range assigned by the composer for this dataset. As an example, in the piece, *Earth System Allegro*, the Drake Passage current was assigned a pitch range between 72 and 96, as shown in fig.2. Once the set of possible integer pitches for a given chord or scale has been produced using the methods described above, the in-scale MIDI pitch with this smallest distance to this rational number pitch is used. As mentioned earlier, the pitch of the MIDI notes must be an integer, as there is no capability in MIDI for notes to sit between values on the chromatic scale. The choice of scale is provided in the piece's settings and is an artistic choice made by the composer. Furthermore, instead of using a single chord or scale for a piece, it is also possible to use a repeating pattern of chords or a chord progression. The choice of chords, and the order of chords are different for each piece. In addition, the number of beats between chord changes, and the number of notes per beat are also assigned in the settings. Furthermore, each track in a given piece may use a different chord progression.

The velocity of notes is determined using a similar method to pitch: the time series data are converted into velocities such that the lowest value in the dataset is the quietest value available, and the highest value of the dataset is the loudest value available. The notes in between are assigned proportionally by their data value between the quietest and loudest notes. Each track may have its own customised velocity range, such that any given track may be louder or quieter than the other tracks in a piece. The choice of dataset used to determine velocity is provided in the settings. We rarely used the same dataset for both pitch and for velocity. This is because it results in the high pitch notes being louder and the low pitch notes being quieter.

After binning the notes into the appropriate scales, all notes are initially the same duration. If the same pitched note is played successively, then the first note's duration is extended and the repeated notes are removed.

A smoothing function may also be applied to the data before the dataset is converted into musical notes. Smoothing means that it is more likely that the same pitched note will be played successively, so a track with a larger smoothing window will have fewer notes than a track with a smaller window. From the musical perspective, smoothing slows down the piece by replacing fast short notes with longer slower notes. Smoothing can also be used to slow down the backing parts to highlight a faster moving melody. Nearly all the pieces described here used a smoothing window.

After applying this method to multiple tracks, they are saved together in a single MIDI file using the python MIDITime library, (Corey, 2016) Having created the MIDI file, the piece is performed by the TiMidity++ digital piano, (Izumo and Toivonen, 2004), which converts the MIDI format into a digital audio performance in the MP3 format. In principle, it should be possible to use alternative MIDI instruments, but for this limited study we exclusively used the TiMidity++ digital piano. Where possible, the MIDI files were converted into sheet music PDF files using the musescore software, (Musescore BVBA, 2019). However, it is not possible to produce sheet music for all six pieces, as some have too many MIDI tracks to be converted to sheet music by this software.

Each piece has a diverse range of settings and artistic choices made by the composer: the choice of datasets used to determine pitch and velocity for each track, the pitch and velocity ranges for each track, the piece's tempo and the number of notes per beat, the musical key and chord progression for each track, and the width of the smoothing window. The choice of instrument is also another artistic choice, although in this work, only one instrument was used, the TiMidity+ piano synthesizer. As a whole, these decisions allow the composer to attempt to define the emotional context of the final piece. For instance, a fast-paced piece in a major progression may sound happy and cheerful to an audience who are used to associating fast-paced songs in major keys with happy and cheerful environments. It should be mentioned that there are no strict rules governing the emotional context of chords, tempo or instrument and the emotional contexts of harmonies, timbres and tempos differ between cultures. Nevertheless, through exploiting the standard behaviours of western musical traditions, the composer can attempt to imbue the piece with emotional musical cues that fit the theme of the piece or the behaviour of the underlying climate data.

To create a video, we produced an image for each time step in each piece. These figures show the data once they have been converted and binned into musical notes, using units of the original data. A still image from each video is shown in fig. 4. The ffmpeg video editing software, (FFmpeg Developers, 2017), was used to convert the set of images into a video and added the MP3 as the soundtrack.

The finished videos were uploaded onto the lead author's YouTube channel, (de Mora, 2019).

4 Works

Six pieces were composed, generated and published using the methods described here. These pieces and their web addresses are:

Earth System Allegro: https://www.youtube.com/watch?v=RxBhLNPH8ls

Pre-industrial Vivace: https://www.youtube.com/watch?v=Hnkvkx4BMk4

Ocean Acidification in E minor: https://www.youtube.com/watch?v=FPeSAA38MjI

Sea Surface Temperature Aria: https://www.youtube.com/watch?v=SYEncjETkZA

Giant Steps Spin Up: https://www.youtube.com/watch?v=fSK6ayp4i4w

Seven Levels of Climate Change: https://www.youtube.com/watch?v=2YE9uHBE5OI

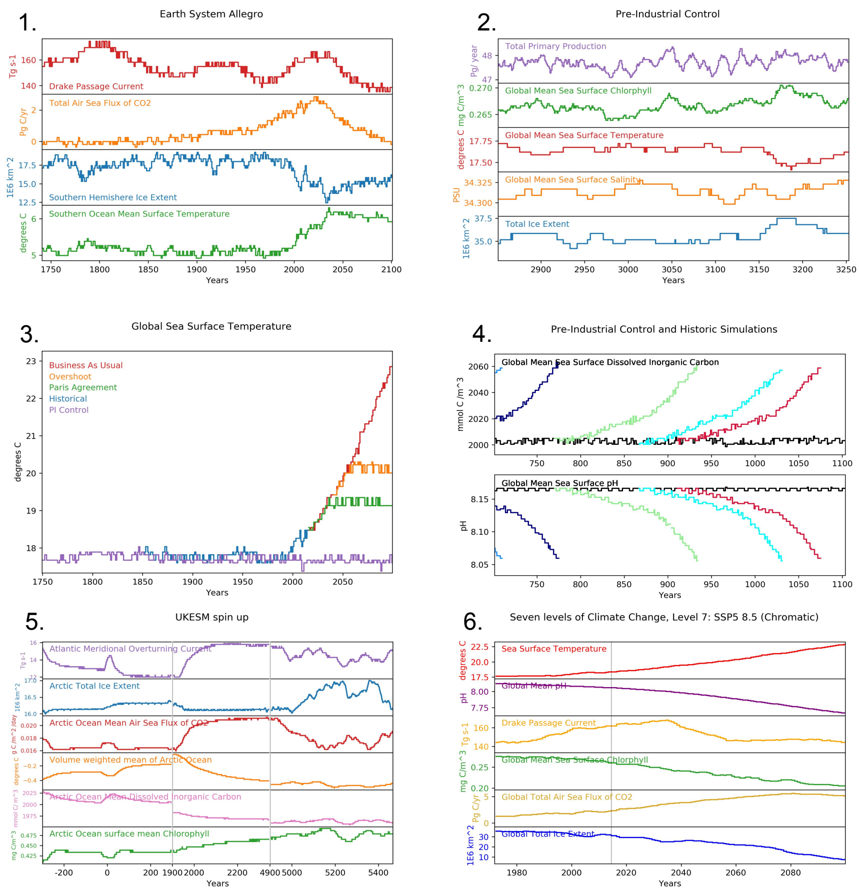

Figure 4. The final frame of each of the six videos. These frames of the videos are shown in the order that they were published. The videos 1), 3), 5) and 6) use a consistent x-axis for the duration of the video, but videos 2) and 4) have rolling x-axes that change over the course of the video. This means that panes 2 and 4 show only a small part of time range. Pane 5 includes two vertical lines showing the jumps in the spin up piece. Pane 6 shows a single vertical line for the crossover between the historical and future scenarios.

The main goals of the work were to generate music using climate model data, and to use music to illustrate some standard practices in Earth System modelling that might not be widely known outside our community Beyond these broader goals, each piece had its own a unique goal: to demonstrate the principles of sonification using UKESM1 data in the *Earth System Allegro*. The *Pre-industrial Vivace* introduces the concept of a pre-industrial control simulation and highlights how an emotional connection can be made between the model output and the sonification of the data. The *Sea Surface Temperature Aria*'s goal was to demonstrate the range of behaviours of the future climate projections. *Ocean Acidification in E minor* aimed to show the impact of rising atmospheric CO_2 on ocean acidification and also to illustrate how historical runs are branched from the pre-industrial control. The *Giant Steps Spin Up* shows the process of spinning up the marine component of the UKESM1, and finally, the *Seven Levels of Climate Change* was aiming to use the musical principles of jazz harmonisation to distinguish the full set of UKESM1's future scenario simulations.

These six pieces are summarised in fig. 4 and tab. 1. Figure 4 shows the final frame of each of the pieces, tab. 1 shows the summary information about each of the videos, including the publication date, the duration and lists the experiments and datasets used to generate the piece.

4.0.1 Earth System Allegro

The *Earth System Allegro* is a relatively fast-paced piece in C Major, showing some important metrics of the Southern Ocean in the recent past and projected into the future with the shared socioeconomic pathway (SSP) scenario, SSP1 1.9. The SSP1 1.9 projection is the future scenario in which the anthropogenic impact on the climate is the smallest. The C major scale is composed of only natural notes (no sharp or flat notes), making it one of the first chords that people encounter when learning music. In addition, major chords and scales like C major typically sound happy. Christian Schubart's 'Ideen zu einer Aesthetik der Tonkunst' (1806) describe C major as "Completely pure. Its character is: innocence, simplicity, naivety, children's talk." Through choosing C major and an upbeat tempo, and data from the best possible climate scenario (SSP1 1.9), we aimed to start the project with a piece with a sense of optimism about the future climate and to introduce the principles of musification of UKESM1 time series data.

The Drake Passage current, shown in red in the top left pane of fig. 4, is a measure of the strongest current in the ocean, the Antarctic circumpolar current. This is the current that flows eastwards around Antarctica. The second dataset shown here in orange is the global total air to sea flux of CO_2. This field shows the global total atmospheric carbon dioxide that is absorbed into the ocean each year. Even under SSP1 1.9, UKESM1 predicts that this value would rise from around zero during the pre-industrial period to a maximum of approximately 2 Pg of carbon per year around the year 2030, followed by a return to zero at the end of the century. The third field is the sea ice extent of the Southern Hemisphere, shown in blue. This is the total area of the ocean in the Southern Hemisphere which has more that 15% ice coverage per grid cell of our model. The fourth field is the Southern Ocean mean surface temperature, shown in green, which rises slightly from approximately 5 degrees Celsius in the pre-industrial period up to a maximum of 6 degrees. The ranges of each dataset are illustrated in fig. 2.

In this piece, the Drake Passage current is set to the C major scale, but the other three parts modulate between the C major, G major, A minor and F major chords. These are the first, fifth, sixth and fourth chords in the root of C major. This progression is strikingly popular and may be heard in songs such as: *Let It Be*, by the Beatles, *No Woman No Cry* by Bob Marley and the Whalers, *With or Without You* by U2, *I'm Yours* by Jason Mraz, *Africa* by Toto, among many others. By choosing such a common progression, we were aiming to introduce the concept of musification of data using familiar sounding music and to avoid alienating the audience.

4.0.2 Pre-industrial Vivace

The *Pre-industrial Vivace* is a fast-paced piece in C Major, showing various metrics of the behaviour of the Global Ocean in the pre-industrial control run. The pre-industrial control run is a long term simulation of the Earth's climate without the impact of the industrial revolution or any of the subsequent human impact on climate. At the time that the piece was created, there were approximately 1400 simulated years. We use the control run as starting points for historical simulations, but also to compare the difference between human-influenced and simulations of the ocean without any anthropogenic impact.

The final frame of the *Pre-industrial Vivace* video is shown in the top right pane of fig. 4. The top pane of this video shows the global marine primary production in purple. The primary production is a measure of how much marine phytoplankton is growing. Similarly, the second pane shows the global marine surface chlorophyll concentration in green; this line rises and falls alongside the primary production in most cases. The third and fourth panes show the global mean sea surface temperature and salinity in red and orange. The fifth pane shows the global total ice extent. These five fields are an overview of the behaviour of the pristine natural ocean of our Earth System model. There is no significant drift and there is no long term trend in any of these fields. However, there is significant natural variability operating at decadal and millennial scales.

As with the *Earth System Allegro*, *Pre-industrial Vivace* uses the familiar C major scale but adds a slight variation to the chord progression. The first half of the progression is C major, G major, A minor and F major, but it follows with a common variant of this progression: C major, D minor, E minor and F major. Through using the lively vivace tempo and a familiar chord progression in a major key, this piece aims to use musification to link the pre-industrial control simulation with a sense of happiness and ease. The lively, fast, jovial tone of the piece should match the pre-industrial environment which is free running and uninhibited by anthropogenic pollution.

4.0.3 Sea Surface Temperature Aria

The *Sea Surface Temperature Aria* demonstrates the change in the sea surface temperature in the pre-industrial control run, the historical scenario and under three future climate projection scenarios, as shown in pane 3 of fig. 4. The first scenario is the "business as usual" scenario, SSP5 8.5, where human carbon emissions continue without mitigation shown in red. The second scenario is an "overshoot" scenario, SSP5 3.4-overshoot, where emissions continue to grow, but then drop rapidly in the middle of the 21^{st} century, shown in orange. The third scenario is SSP1 1.9, labelled as the "Paris Agreement" scenario, where carbon emissions drop rapidly from the present day, shown in green. The goal of this piece is to demonstrate the range of differences between some of the SSP scenarios on sea surface temperature.

The pre-industrial control run and much of the historical scenario data are relatively constant. However, they start to diverge in the 1950s. In the future scenarios, the three projects all behave similarly until the 2030s, then the SSP1 1.9 scenario branches off and maintains a relatively constant global mean sea surface temperature. The SSP5 3.4 scenario's SST continues to grow until the year 2050, while the SSP5 8.5 scenario's SST grows until the end of the simulation.

Musically, this piece is consistently in the scale of A minor harmonic with no modulating chord progression. The minor harmonic scale is a somewhat artificial scale in that it augments 7^{th} note of the natural minor scale. The augmented 7^{th} means that there is a minor third between the 6^{th} and 7^{th} note, making it sound uneasy and sad (at least to the author's ears). An aria is a self-contained piece for one voice, normally within a larger work. In this case, the name aria is used to highlight that only one dataset, the sea surface temperature, participates in the piece. This piece starts relatively low and slow, then grows higher and louder as the future scenarios are added to the piece. The unchanging minor harmonic chord, slow tempo and pitch range were chosen to elicit a sense of dread and discord as the piece progresses to the catastrophic SSP5 8.5 scenario at the end of the 21^{st} century.

4.0.4 Ocean acidification in E minor

Ocean acidification in E minor demonstrates the standard modelling practice of branching historical simulations from the pre-industrial control run, as well as the impact of rising anthropogenic carbon on the ocean carbon cycle. The final frame of this video is shown in pane 4 of fig. 4. The top pane shows the global mean dissolved inorganic carbon (DIC) concentration in the surface of the ocean and the lower pane shows the global mean sea surface pH. In both panes, the pre-industrial control run data are shown as a black line and the coloured lines represent the fifteen historical simulations.

This piece uses a repeating *12-bar blues* structure in E minor and a relatively fast tempo. This chord progression is an exceptionally common progression, especially in blues, jazz and early rock and roll. It is composed of four bars of the E minor, two bars of A minor, 2 bars of E minor, then one bar of B minor, A minor, E minor and B minor. The twelve bar blues can be heard in songs such as: *Johnny B. Goode* by Chuck Berry, *Hound Dog* by Elvis Presley, *I got you (I feel Good)* by James Brown, *Sweet Home Chicago* by Robert Johnson or *Rock n Roll* by Led Zeppelin. In the context of Earth System Music, the 12-bar pattern with its opening set of four bars, then two sets of two bar and ending for four sets of one bar between key changes drives the song forward before starting again slowly. This behaviour is thematically similar to the behaviour of the ocean acidification in UKESM1 historical simulation, where the bulk of the acidification occurs at the end of each historical period.

This video highlights that the marine carbon system is heavily impacted over the historical period. In the pre-industrial control runs, both the pH and the DIC are very stable. However, in all historical simulations with rising atmospheric CO_2, the DIC concentration rises and the pH falls. The process of ocean acidification is relatively simple and well understood (Caldeira and Wickett, 2003; Orr et al., 2005). The atmospheric CO_2 is absorbed from the air into the ocean surface, which releases hydrogen ions into the ocean, making the ocean more acidic. The concentration of DIC in the sea surface is closely linked with the concentration of atmospheric CO_2, and it rises over the historic period. This behaviour was observed in every single UKESM1 historical simulation.

This video also illustrates an important part of the methodology used to produce models of the climate that may not be widely known outside our community. When we produce models of the Earth System, we use a range of points of the pre-industrial control as the initial conditions for the historical simulations. All the historical simulations have slightly different starting points, and evolve from these different initial conditions, which gives us more confidence that the results of our projections are due to changes since the pre-industrial period instead of simply a consequence of the initial conditions. In this figure, the historical simulations are shown where they branch from the pre-industrial control run instead of using the "real" time as the x-axis.

4.0.5 Giant Steps Spin Up

This piece combines the spin up of the United Kingdom Earth System Model with the chord progression of John Coltrane's *Giant Steps*, (Coltrane, 1960). The spin up is the process of running the model from a set of initial condition to an equilibrium steady state. When a model reaches a steady state, this means that there is no significant trend or drift in the mean behaviour of several key metrics. For instance, as part of the C4MIP protocol, Jones et al. (2016) suggest a drift criterion of less than 10 Pg of carbon per century in the absolute value of the flux of CO_2 from the atmosphere to the ocean. In practical terms, the ocean model is considered to be spun up when the long-term average of the air sea flux of carbon is consistently between -0.1 and 0.1 Pg of carbon per year.

The spin up is a crucial part of model development. Without spinning up, the historical ocean model would still be equilibrating with the atmosphere. It would be much more difficult to separate the trends in the historical and future scenarios from the underlying trend of a model still trying to equilibrate. Note that while a steady state model does not have any significant long term trends or drifts; it can still have short term variability. This short term variability can be seen in the pre-industrial simulation in the *Pre-industrial Vivace* piece. It can take a model thousands of years of simulation for the ocean to reach a steady state. In our case, the spin up ran for approximately 5000 simulated years before the spun up drift criterion was met (Yool et al.).

The UKESM1 spin up was composed of several phases in succession. The first stage was a full coupled run using an early version of UKESM1. Then, an ocean-only run was started using a 30 year repeating atmospheric forcing dataset. The beginning of this part of the run is considered to be the beginning of the spin up and the time axis is set to zero at the start of this run. This is because the early version of UKESM1 did not include a carbon system in the ocean. After about 1900 years of simulating the ocean with the repeating atmospheric forcing dataset, we had found that some changes were needed to the physical model. At this point, we initialised a new simulation from the final year of the previous stage and changed the atmospheric forcing. This second ocean-only simulation ran until the year 4900. At the point, we finished the spin up with a few hundred years of fully coupled UKESM1, with ocean, land, sea ice and atmosphere models. Due to the slow and repetitive native of the ocean-only spin up, several centuries of data were omitted. These are marked as grey vertical lines in the video and in the bottom left pane of fig. 4.

The piece is composed of several important metrics of the spin up in the ocean, such as the Atlantic meridional overturning current (purple), Arctic ocean total ice extent (blue), the global air sea flux of CO_2 (red), the volume weighted mean temperature of the Arctic ocean (orange), the surface mean DIC in the Arctic Ocean (pink) and the surface mean chlorophyll concentration in the Arctic ocean (green).

The music is based on the chord progression from the jazz standard, John Coltrane's *Giant Steps*, although the musical progression was slowed to one chord change per four beats instead of a change every beat. This change occurred as an accident, but we found that the full speed version sounded very chaotic, so the slowed version was published instead. This piece was chosen because it has a certain notoriety due to the difficulty for musicians to improvise over the rapid chord changes. In additional, *Giant Steps* was the first new composition to feature Coltrane changes. Coltrane changes are a complex cyclical harmonic progression, which forms a musical framework for jazz improvisation. We hoped that the complexity of the Earth system model is reflected in the complexity of the harmonic structure of the piece. The cyclical relationship of the Coltrane changes also reflects the 30 year repeating atmospheric forcing dataset used to spin up the ocean model.

4.0.6 Seven Levels of Climate Change

This piece is based on a YouTube video by Adam Neely, called The 7 Levels of Jazz Harmony, (Neely, 2019). In that video, Neely demonstrates seven increasingly complex levels of jazz harmony by re-harmonising a line of the chorus of Lizzo's song *Juice*. We have repeated Neely's re-harmonisation of *Juice* here, such that each successive level's note choice is informed by Earth System simulations with increasing levels of emissions and stronger anthropogenic climate change.

At the time of writing, UKESM1 had produced simulations of seven future scenarios. The seven scenarios of climate change and their associated Jazz harmony are:

- Level 0 : Pre industrial control - Original Harmony
- Level 1 : SSP1 1.9 - 4 note chords
- Level 2 : SSP1 2.6 - Tritone substitution
- Level 3 : SSP4 3.4 - Tertiary harmony extension
- Level 4 : SSP5 3.4 (overshoot) - Pedal Point
- Level 5 : SSP2 4.5 - Non-functional harmony
- Level 6 : SSP3 7.0 - Liberated dissonance
- Level 7 : SSP5 8.5 - Fully chromatic

Note that we were not able to reproduce Adam's seventh level: intonalism or xenharmony. In this level, the intonation of the notes are changed depending on the underlying melody. Unfortunately, the MIDITime python interface to MIDI has not yet reached such a level of sophistication. Instead, we simply allow all possible values of the 12 note chromatic scale.

The datasets used in this piece are a set of global scale metrics that show the bulk properties of the model under the future climate change scenarios. They include the global mean SST (red), the global mean surface pH (purple), the Drake Passage current (yellow), the global mean surface chlorophyll concentration (green), the global total air to sea flux to CO_2 (gold) and the global total ice extent (blue). As the piece progresses through the seven levels, the anthropogenic climate change of the model becomes more extreme, matching the increasingly esoteric harmonies of the music.

5 Limitations and potential extensions

We have successfully demonstrated that it is possible to generate music using data from the UK's Earth system Model. We have also shown that we can use illustrate some standard practices in Earth System modelling using music. Within the framework of this pilot study, we must also raise some limitations and suggest some possible extensions for future versions of this work.

A significant omission of this study is the measurement of the impact, the reach or the engagement of these works. We did not test whether the audience was composed of laymen or experts. We did not investigate whether the audience learned anything about Earth System modelling through these series of videos. We did not monitor the audience reactions or interpretations of the music. Future extensions of this project should include a survey of the audience, investigating their backgrounds, demographics, what they learned about Earth System models and their overall impressions of the pieces. This could take the form of an online survey associated with each video, or a discussion with the audience at a live performance event.

In addition, in this work, we make no effort to monitor or describe the reach of the YouTube videos, track comments, subscriptions or the source of the views. While some tools are available for monitoring the number of videos within YouTube's content creator toolkit, YouTube Studio (Google, 2019), a preliminary investigation found that it was not possible to use these tools alone to create a sufficiently detailed analysis of the impact, reach, or dissemination of these music creation method. YouTube Studio currently includes some demographic details, including gender, country of origin, viewership age, and traffic source but it is not sufficient for an audience survey. This toolkit was built to help content creators monitor and build their audience and to monetise videos using advertisements. It is not fit for the purpose of scientific engagement monitoring. For instance, it was not possible to use YouTube Studio to determine: the expertise of the audience, their thoughts on climate change, whether they read the video description section, whether they understood the description. Some of these features could be added to YouTube by Google, but many of them would require the audience survey described above.

Our videos only include the music and a visualisation of the data, they do not include any description about how the music was generated or the Earth system modelling methods used to create the underlying data. The explanations of the science and musification methodologies are held in a text description below the video. Furthermore, viewers must expand this box by clicking the "show more" button. Using the tools provided in YouTube studio, it is not currently possible to determine whether the viewers have expanded, read or understood the description section. When we have shown these videos to live audiences at scientific meetings and conferences, it has always been associated with a brief explanation of the methods. In the future, this explanatory preface to the work could be included in the video itself or as a separate video, in addition to below the video in the description section. This would likely increase the audience's understanding of our music generation process.

If additional pieces were made, there are several potential ways that the methodology used to create them could improved relative to the methods used to create the initial set of videos. In future versions of this work, it should be possible to use ESMValTool (Righi et al., 2019) to produce the time series data instead of BGC-val. This would make the production of the time series more easily repeatable, but also would also make it easier for pieces to be composed using data available in CMIP5 and CMIP6 coupled model intercomparison projects. This broadens the scope of data by allowing other models, other model domains including the atmosphere and the land surface, and even observational datasets. For instance, we could make a multimodel intercomparison piece, or a piece based on the atmospheric, terrestrial and ocean components of the same model. In addition, using ESMValTool would also make it more straightforward to distribute the source code that was used to make these pieces.

In their reflections on auditory graphics, Flowers (2005) lists several “Things that work” and “Approaches that do not work”. From the list of things that work, we included four of the five methods that worked: pitch coding of numeric data, the exploitation of temporal resolution of human audition, manipulating loudness changes, and using time as time. We were not able to include the selection of distinct timbres to minimise stream confusion. From the list of approaches that do not work, we successfully avoided several of the pitfalls, notably pitch mapping to continuous variables, using loudness changes to represent an important continuous variable. However, we did include one of the approaches that Flowers did not recommend: we simultaneously plot several variables with similar pitches and timbres. However, it is worth noting that maximising the clarity of the sonification is the goal of Flowers (2005), but our focus was to produce and disseminate some relatively listenable pieces of music using UKESM1 data.

The two Flowers (2005) suggestions that we failed to address were both related to using the same timbre digital piano synthesizer for all data. Due to the technical limitations of using TiMidity++, we were not able to vary the instruments used, and thus there was very little variability in terms of the timbres. These pieces were all performed by the same instrument, a solo piano, which limits the musical diversity of the set of pieces. In addition, each dataset in a given piece was performed by the same instrument, making it difficult to distinguish the different datasets being performed simultaneously. Further extensions of this work could use a fully featured digital audio workstation to access a range of digital instruments beyond the digital piano, such as a string quartet, a horn and woodwind section, a full digital orchestra, electric guitar and bass, percussive instruments, or electronic synthesised instruments. This would comply with the suggestions listed in Flowers (2005), allowing the individual datasets to stand out musically from each other in an individual piece, but would also lead to a much more diverse set of musical pieces.

From a musical perspective, there are many ways to improve the performances of the pieces for future versions of this work. As raised in the comments from social media, a human pianist would be able to add a warmth to the performance that is beyond the abilities of MIDI interpreters. A recording of a human performance could also add the hidden artefacts of live recording, such as room noise, stereo effects, and natural reverb. On the other hand, due to the nature of the process used to generate these pieces, it is possible that it may not be possible for a single human to perform several of the pieces due to the speed, complexity, number of simultaneous notes or the range of these pieces. Alternatively, it may be possible to “humanise“ the MIDI by making subtle changes to the timing and velocities of the MIDI notes. This is a recording technique that can take a synthesised perfectly timed beat and make it sound like it is played by a human. It does this by moving the individual notes slightly before or after the beat, and adding subtle variations in the velocity (John Walden, 2017). Also, TiMidity++ uses the same piano sample for each pitch. This means that when two tracks of a piece play the same pitch at the same time, the exact same sample is played twice simultaneously. These two identical sample sound waves are added constructively and the note jumps out much louder than it would be if a human played the part. A fully featured digital piano or a human performance would remove these loud jumps, but also be able to add more nuance and warmth to the performance. Finally, the published pieces had no mastering or post-production. Even a basic mastering session by a professional sound engineer would likely improve the overall quality of the sound of these pieces.

In terms of the selection of chords progression, tempo, and rhythms, it may be possible to target specific audiences using music based on popular artists or genres. For instance, the reach of a piece might be increased by responding to viral videos or by basing a work on a popular trending song.

In these works, we have focused on reproducing western musical, both traditional and modern, in order to connect each piece with the associated emotional musical cues. Alternatively, there is a significant diversity of traditional and modern styles of music from other regions around the world; a much wider range of rhythms, timbres, styles and emotional cues could be exploited in future extensions of this work.

With regards to the visual aspect of these videos, it should be straightforward to improve the quality of the graphics used. The current videos only show a simple scalar field as it develops over time. They could be improved by adding animated global maps of the model, interviews or live performances to the video. It may also be a positive addition to preface the videos with a brief explanation of the project and the methods deployed. On the technical side, there may also be some visual glitches and artefacts which arise due to YouTube's compression or streaming algorithms. A different streaming service or alternative video making software might help remove these glitches.

YouTube videos are typically shown in the suggestions queue with a thumbnail image and the video title. The thumbnail is the graphic placeholder that shows the video while it is not playing, on YouTube as a suggested video, or in the Facebook or Twitter feeds. The thumbnail is how viewers first encounter the video and it is a crucial part of attracting an audience. There are lots of guides helping create better thumbnails (Kjellberg and PewDiePie, 2017; Video Influencers, 2016; Myers, 2019). Future works should attempt to optimise the video thumbnail to attract a wider audience.

While we did not investigate the reach or dissemination of these pieces in this work, if the goal of future projects were to increase the online audience size, it might be possible to reach a wider audience using a press release, a public showing of the videos, a scheduled publication date, or through a collaboration with other musicians or YouTube content creators. It may also be possible to host a live concert, make a live recording, or broadcast a YouTube live stream. It is not fully understood how a video can go viral, but it has been shown view counts can rise exponentially when a single person or organisation with a large audience shares a video (West, 2011; Jiang et al., 2014). Improvements to the music, the video, the description and the thumbnail make it more likely for such an influencer with large audience to like, share, or re-tweet a piece, which could result in an significant increase in the audience size and view count. The videos in this work were posted online in an ad hoc fashion, as soon as they were finished. To maximise the number of views, experts have recommended consistent, scheduled in advance, weekly videos, and it has been advised to publish them late in the week in the afternoons (Katie Nohr, 2017; Think Media, 2017). Finally, it should be possible to increase the reach of this work through paid advertising on YouTube and other social media platforms. This would place the videos higher in the suggested video rankings and on the discovery queues.

6 Conclusions

In this work, we took data from the first United Kingdom Earth System Model and converted it into six musical pieces and videos. These pieces covered the core principles of climate modelling or ocean modelling: pre-industrial control runs, the spin up process, the multiple future scenarios, the Drake Passage current, the air sea flux of CO_2 or the Atlantic meridional overturning circulation. While limited to a single instrument, the synthesised piano, they included a range of musical styles, including classical, jazz, blues and contemporary styles.

While the wider public are likely to be familiar with climate change, they are less likely to be familiar with our community's methods. In fact, many standard tools in the arsenal of climate modeller may not be widely appreciated outside our small community, even within the scientific community. These six musical pieces open the door on a new, exciting and fun approach to how we engage with the fellow scientists and the wider public.

We have also discussed some ways to improve future iterations of this pilot study. Future works could be performed to an live audience, we could collaborate with musicians, and the viewership would likely be increased with improved video graphics, thumbnails, live performances, video diversity, and more frequent upload rates. The scientific content of the videos could be expanded by accessing new datasets, other parts of the UKESM1 Earth System, other CMIP models, or observational datasets. The quality of the music could be improved by including additional instruments and musical genres, and by making live recordings instead of MIDI performance. The knowledge transfer aspect of the project could be improved upon by appending explanations of the science to the video, and by surveying the audience to identify the impact of these works.

Finally, the authors would like to encourage other scientists to think about how their work may be sonified. You may have beautiful and unique music hidden within your data; the methods described in this work would allow it to be made manifest.

Data availability. The sheet music for four pieces and the MIDI files for all six pieces are available alongside this publication.

Video supplement. These videos are published online in the YouTube channel: https://www.youtube.com/c/LeedeMora.

Author contributions. LdM used BGC-val to produce the model time series data, sonified the BGC-val data, published the videos and prepared the text. AAS, RSS and JW provided feedback and early discussions on music in ESM, AY, JP, TK helped develop the core time series data sets in UKESM1, RJP shared the finished videos and provided audience feedback, JCB and CGJ lead the PML modelling group and UKESM1 projects, respectively and both provided crucial feedback and support.

Competing interests. Like most YouTube content creators, LdM has a financial relationship with YouTube. However, at the time of writing, the channel in which these videos were posted did not meet YouTube's monetisation requirements (1000 subscribers and 4000 hours watched).

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Table 1. Table showing the video publication details, including the publication date, the duration, the CMIP experiment names and the datasets used.

Video title	**Publication date**	**Duration,** Minutes:seconds	**Experiments**	**Datasets**
Earth System Allegro RxBhLNPH8ls	21-08-2019	1:02	Historical, SSP1 2.5	Drake Passage current, Total Air sea flux of CO_2, Southern Hemisphere ice extent, Southern Ocean SST
Pre-industrial Vivace Hnkvkx4BMk4	21-08-2019	2:27	PI Control	Total Primary Production, Global mean sea surface ch SST, SSS, Total ice extent
Ocean Acidification in E minor FPeSAA38MjI	22-08-2019	1:56	PI control, historical	Global mean surface DIC, Global mean surface mean pH
Sea Surface Temperature Aria SYEncjETkZA	02-09-2019	1:17	PI control, historical, SSP1 1.9, SSP5 3.4 OS, SSP5 8.5	Global mean SST
Giant Steps Spin Up fSK6ayp4i4w	13-09-2019	2:52	Spin up	Atlantic meridional overturning current, Arctic Ice exte Arctic mean air sea flux of CO_2, Volume weighted mean temperament of the Arctic ocea Global surface mean DIC, Mean surface chlorophyll in the
Seven Levels of Climate Change 2YE9uHBE5OI	14-10-2019	2:55	PI control, historical, SSP1 1.9, SSP1 2.6, SSP4 3.4, SSP5 3.4 - overshoot, SSP2 4.5, SSP3 7.0, SSP5 8.5	Global mean SST, pH, Drake Passage current, Global mean surface chlorophyll, Global total Air sea flux of CO_2, Global total Ice extent