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Dear Geoscientific Communication editors, referees and reviewers,

We received two review comments and one short comment. We have addressed their comments in this document, and made changes to the main document, also attached. We're like to thank both anonymous referees and the short comment author for their helpful comments. Thanks to their contributions, this work is in a much better state and should be easier to follow.

For clarity, we will reproduce the comments and respond to them in turn. Our responses are marked in bold and begin with **"LdM:".** The new text are included with an indent and may include some latex grammar. Alternatively, a document showing the difference between the old and the new version is also available.

Sincerely,

Lee de Mora – representing the authorship team.

Anonymous Referee #1

The article is well written and very interesting. Below we provide feedback to the author's that we hope is useful. This was co-reviewed by myself and a colleague, and we ourselves are a science-art collaborative team. This co-review of the article was agreed by Editor Sam Illingworth.

LdM: Thank you both for your review and for the kind words. Also, thanks to Sam for allowing this novel team review approach.

1. As this is a pilot study, it is clear why only one tool was utilised to gather and analyse data towards the reach, engagement and audience of the channel and the videos. Nevertheless, it would be very useful for readers and those who might like to expand on this methodology and methods if the choice to not triangulate the data was stated as one of the limitations, and discussed. You could highlight in the introduction that this is a pilot study, stating it explicitly, and then follow-up with a brief discussion about the experimental character of the research and why in this instance the focus was not on triangulating findings, but to present the study. If you are planning additional evaluation and analyses it would be useful to highlight that, even if briefly, in the discussion.

LdM: At the request of referee #2, we added a limitations section. That goes into more detail about this. We've also added a short paragraph to the introduction to explicitly point out that this is a pilot study.

> It should be noted that this work is an early pilot study. The aims of the project are outlined below in sect.~\ref{sec:works}. The limitations of this approach are outlined in sect.~\ref{sec:limitations}.

2. The authors' choices for tempo, genre, and scale of each composition (allegro, vivace, aria etc.) adds to the "emotional connection" mentioned in line 213. There is value in the authors elaborating on these choices, and to explain if the reason of each choice is due to the feeling that the data are expressing. For example, for Earth System Allegro, one can notice that the authors describe it as "[. . .] a future scenario in which the anthropogenic impact on the climate is at a minimum" (line 225). This could be perceived as a happy scenario, and is potentially why the authors aligned it with the allegro rhythm, because allegros are usually lively and merry tempos, able to express and communicate positive and happy scenarios. It would add richness to the methods and explanation of data interpretation for the reader if more details like those that I expressed above could be included in the descriptions of all the pieces.

LdM: We have added additional explanations of how the artistic choices were made for each piece in their descriptions. These are:

> 3.1.1 Earth System Allegro
>
> 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." As this was the first piece in the series, the link between

this seemed an appropriate way to start the Earth System Music project. 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.

In this piece, the Drake Passage current is set to the C major scale, but the other three parts module 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: \textit{Let It Be}, by the Beatles, \textit{No Woman No Cry} by Bob Marley and the Whalers, \textit{With or Without You} by U2, \textit{I'm Yours} by Jason Mraz, \textit{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.

3.1.2 Pre-industrial Vivace

As with the \textit{Earth System Allegro}, \textit{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 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.

3.1.3 Sea Surface Temperature Aria

Musically, this piece is consistently in the scale of A minor harmonic with no chord progression. The minor harmonic scale is a somewhat artificial scale in that it augments 7th note of the natural minor scale. The augmented 7th means that there's a minor third between the 6th and 7th 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 when looking towards the catastrophic SSP5 8.5 scenario.

3.1.4 Ocean acidification in E minor

This piece uses a repeating \textit{12 bar blues} structure in E minor and a relatively fast tempo. This chord progression is an exceptionally common progression, especially in early 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 be heard in songs such as: \textit{Johnny B. Goode} by Chuck Berry, \textit{Hound Dog} by Elvis Presley, \textit{I got you (I feel Good)} by James Brown,

\textit{Sweet Home Chicago} by Robert Johnson or \textit{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.

3.1.5 Giant Steps Spin Up

The music is based on the chord progression from the jazz standard, John Coltrane's \textit{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, \textit{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.

3.1.6 Seven Levels of Climate Change

As the piece progresses through the seven levels, the behaviour of the model becomes more extreme, matching the increasingly esoteric harmonies of the music.

3. More specifically, in the Quantification of Reach section more detail could be provided to support the evaluation component of this work. We recognize this is a pilot study, but even then there is the potential to include perspectives shared by others (qualitative data), and to use these data as a starting point to build a stronger understanding of how this work is 'reaching' others. For example, you didn't include data on shares or people's comments or shared perceptions (qualitative data) about the project as shared through particular social media platforms.

LdM: We have added a section to the results that list all the comments on social media.

The following statement were posted via social media. These were posted directly on the YouTube video page, or on social media posts linking to the video via facebook, twitter and reddit. Note that we have removed emojis and gifs, but otherwise reproduced comments as they originally appeared.

\begin{enumerate}

\item This one was very dramatic.

\item It gets quite dramatic after 1950-60

\item This was submitted as a scientific research paper here, but don't understand what the point is.

\item Wow! That's awesome!

\item Great idea

\item That's Crazy!!

\item Awesome! Personally I was hoping to hear something of the same ilk as system of a down or similar. Does make modelling sound far more upbeat though

\item Brilliant idea! Just like Herman Hess's book 'The Glass bead Game', where data is unified from many sources and brought together by many senses. Listen to how the ocean sings!

\item AMAZING!!!!

\item A total new meaning for the "listen to the ocean" motto

\item That's awesome! Can you post this to someone with a bigass twitter handle. This deserves more attention. Maybe send it to Adam Rutherford at Inside Science?

\item It's quite different from the previous one! Super Cool stuff!!

\item This is amazing. If you can find a setup that would cause noticeable change in the music between pre-industrial and future you're viral

\item I love this!! Well done!

\item This is amazing ! Was initially quite surprised that these weren't more tonally chaotic - then I read I the blurb for the top video. I presume that you could do the same with any choice of key and scale? Also, I hope you realise that, with your choice of C-major, you have made something worthy on inclusion in the next Axis of Awesome medley

\item Certainly very interesting, but it lacks a lot of human touch. These generations don't seem to take into account many compositional techniques that are almost vital to make a comprehensive piece of music, such as motifs, dynamics, musical form, things like that. I found that there wasn't much for the ear to catch onto musically, no clear melodies, rhythms, harmonic progressions etc. Because of this it can also be quite hard for a human to learn, adding on to the challenge of coordinating the strange rhythms between the hands. So it's cool, but very unhuman music and thus most likely difficult for humans to play.

\item I think if humans would take their time to learn this, the musical phrasing they would bring to the table could do a lot to make the pieces easier and more enjoyable to listen to. I think computer made music is very cool in that it really highlights the amount of complexity that goes into creating music as we would know it, namely through the human mind. So the kind of research you're conducting is very valuable indeed!

\item Wow this actually sounds very interesting! Sadly I'm not a very accomplished pianist either, but I'll leave this comment and upvote for visibility.

\end{enumerate}}

And I've expanded the discussion section about the audience

> The comments from social media were listed above in sect.~\ref{sec:results} and were almost all positive and supportive. However, these comments are biased towards the authors friends, family and professional colleagues. These comments include several positive comments and praise, comments about the pieces themselves (``it gets dramatic at 1950-1960``), comparisons to other musicians or works of art (e.g. System of a down, Herman Hess's book Glass bead game, the Axis of Awesome medley), one person ``didn't understand what the point is``, and the final three comments were from a music forum and contain some interesting insight into the musical side of the work. While we hoped to disseminate information about Earth System modelling to a wider audience, it's not possible to determine whether the audience learned anything about Earth System modelling using the metrics provided by YouTube studio or the comments posted on social media. Furthermore, it is not possible to determine whether the audience was composed of laymen or experts. As this was a pilot study, we did not go into greater detail to understand the audience reactions. 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.

While I agree it can be useful to have demographic data, it wasn't clear from the start of the paper that you were interested in the demographic of people that this work reaches.

LdM: I would include the demographics of the audience under the wider term, "reach", which is appears in the abstract and even in the title. Nevertheless, I added the word demographics to the following sentence in the introduction:

> This toolkit allows content creators to monitor the reach, engagement and audience demographics (age, gender, country of origin) for their channel as a whole, as well as for individual videos.

Equally, you report on the nation that YouTube viewers were from in your results, which is fairly limited demographic data, and don't include other data despite having noted its availability in your methods section. From a reader's perspective it isn't only interesting how many people the work reached or who those people are, but also what their perspectives of the work was and any messages that emerged from viewers that could inform our broader understanding about what people took from viewing and experiencing this work. It would help readers to know more about the 'experience' in addition to the 'reach' and the authors could begin to form this with a content analysis of the comments or perspectives shared, and even brief quotes of feedback and perspectives shared by others to offer some insight to people's perspectives.

LdM: We have added the section above and an discussion on the viewer feedback.

4. We include a few more specific questions about the quantification of reach below.

p2 line 52 “provides additional contextual clues to aid the interpretation” Please elaborate on why this happens e.g. the animated graphs provide information usually not available or not attractive enough to read for the general public.

LdM: This paragraph confused two points and was split up to read:

> With the ever-growing interest from the general public towards understanding climate science, it is becoming increasingly important that we present this information in ways accessible to non-experts. It is also becomingly increasingly easier for scientists to use tools such as social media to engage with non-experts audiences and the wider public.

And the section about contextual clues to aid the interpretation was removed.

p7 line 159 “The conversion from model data to musical pitch is performed in two stages. First [. . .]” Please clarify what is the second stage.

LdM: The text here was changed to:

> The conversion from model data to musical pitch is performed in using the following method.

p7 line 164 “[. . .] is an artistic choice” Is there a concept behind that artistic choice each time? Does something trigger the composer to choose a specific scale and not choose another? It help the reader to know if there are any creative or conceptual reasons behind these choices or if it is mostly due to the desirable harmony or aesthetics of the final composition.

LdM: We have expanded following section to the methods section to more accurately describe the role of the artist in creating the piece:

> While the method is relatively straightforward and repeatable, 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. In a scientific context, exploiting the western musical traditions can allow the composer to imbue the piece with the associated emotional musical cues.

p14 line 355 How was the playlist shared?

LdM: The text was changed to:

> Each piece was also added to a YouTube playlist, which was shared via social media in the same way as the individual pieces.

P14 line 341 Note that the authors highlight that most views occurred after the first few days, and this is also presented again in the results. It would be better to highlight this as either an element of the method or as a result, but not as both.

LdM: This fits more in the results section than in the methods section, so it was removed from the methods section.

p14 line 355-57 Please provide reasoning for why broader networks were not engaged and why press releases weren't used to disseminate the research or playlists. This is a primary stream of sharing research, and media teams are trained in helping to guide how research and outputs are shared and delivered to others. Could your reach have been greater had you employed / utilized the resources available through those existing networks? Equally, paying to transmit the research and outputs would likely increase the number of people the work 'reaches', why was this avoided?

LdM: In practice, this was a zero-budget trial study. We were not able to budget the staff time in the communications team, nor were we able to purchase reach through youtube advertising. We have raised these are potential future avenues to reach a wider audience.

The text was changed to:

> As this was a pilot study, there were no particular timed-releases, no press release and no direct assistance from the PML, NERC or UKESM communications teams. The videos were then disseminated through these networks and allowed to reach wider audiences. In addition, no paid advertisements were purchased. Please see sect. 6 for a discussion on possible extensions to this pilot study where these avenues could be explored.

Also note that we plan to produce a press release should this paper be accepted for final publication. That pulibcation and subsequent press release may become a new startring point to count views for this work. We may also time the publication of a new piece to coincide.

If the goal was to get the research to different people then using those tools would assist, and it is then not too surprising that the research was primarily viewed only in the first few days; this could potentially have been overcome by having invested more into the transmission of the research and working with different traditional and social media tools. More explanation is needed as to why different tools weren't used, and potentially for the authors to consider if the approach used to evaluate 'reach' might be better removed from this particular paper that is heavily focused on the methodology and method, and included in a subsequent text that explores evaluation, reach, and viewer experience in greater detail and in a more robust way.

LdM: We have changed to goals to more accurately reflect how we view these works. This work was more of an exploration of the use of music to communicate science rather than an outreach experiment with pre-defined research questions. We learned about it as we went and explored

what was possible. In this work, we hope to explain some of the things that worked and some that didn't for us. It should be noted that none of the authors have experience in outreach research.

p18 line 420 "[. . .] Sea surface temperature aria" Consistency note: The titles are presented in italic and with the initial letter capital throughout the article. Please change to: Sea Surface Temperature Aria.

LdM: Fixed.

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Dear Geoscientific Communication editors, referees and reviewers,

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For clarity, we will reproduce the comments and respond to them in turn. Our responses are marked in bold and begin with **"LdM:".** The new text are included with an indent and may include some latex grammar. Alternatively, a document showing the difference between the old and the new version is also available.

Sincerely,

Lee de Mora – representing the authorship team.

Anonymous Referee #2

This manuscript describes six music pieces that have been produced to make climate data accessible to non-experts. The aims are (1) to generate music pieces using climate model data, (2) to use music to illustrate standard practices in Earth System modelling to non-experts, and (3) to quantify the dissemination of music pieces. The method employed here (i.e., data sonification or turning data into music) is a powerful approach and have been successfully used by others for presenting complex datasets to engage/inspire those outside the expert community. The method is particularly well suited for working with climate data. The authors have done a thorough job of explaining each music video.

LdM: Thank you for the summary and the kind words.

However, there are several sections that need improvements (particularly the method and evaluation). Therefore, I see two major changes:

1. Of the above three goals (also stated in the manuscript), goal 1 was clearly achieved. However, it is not clear how this manuscript addresses goal 2. As for goal 3, there was no systematic, robust documentation of the authors' dissemination strategy, the audience demographics, learning, etc. Therefore, a more quantitative (and systematic) assessment of the video usage is needed. The authors state some strategies for doing this (in discussion and conclusion, e.g., performing to a live audience and surveying the audience to measure impact). I think such strategies are great and should be implemented. It is difficult to indicate if a science communication product is helpful (and if so in what way) without any systematic assessment. Therefore, I highly encourage the authors to consider evaluating their videos, and adding the analysis of their findings to the manuscript.

LdM: We have added more detail to the quantification of reach, results, discussions and limitations sections. There are many changes throughout the paper and we refer the editor and reviewer to the difference document, which lists these changes.

2. The method section (lines 106-192) is difficult to follow for non-musicians. This section explains how the music was produced but fails to explain how it relates to climate data. I think giving some examples may increase its readability. For example, when you state "the lowest value in the dataset is presented by the lowest note. . ." (line 120), it may be helpful to give an example of the lowest value in the dataset (e.g., coldest recorded temperature). The same goes for the highest value in the dataset (line 121).

LdM: We have expanded this whole section and made many clarifications. Unfortunately, music theory is its own discipline (as is music composition) and it's not possible to make a complete, thorough, brief and easy to follow explanation here.

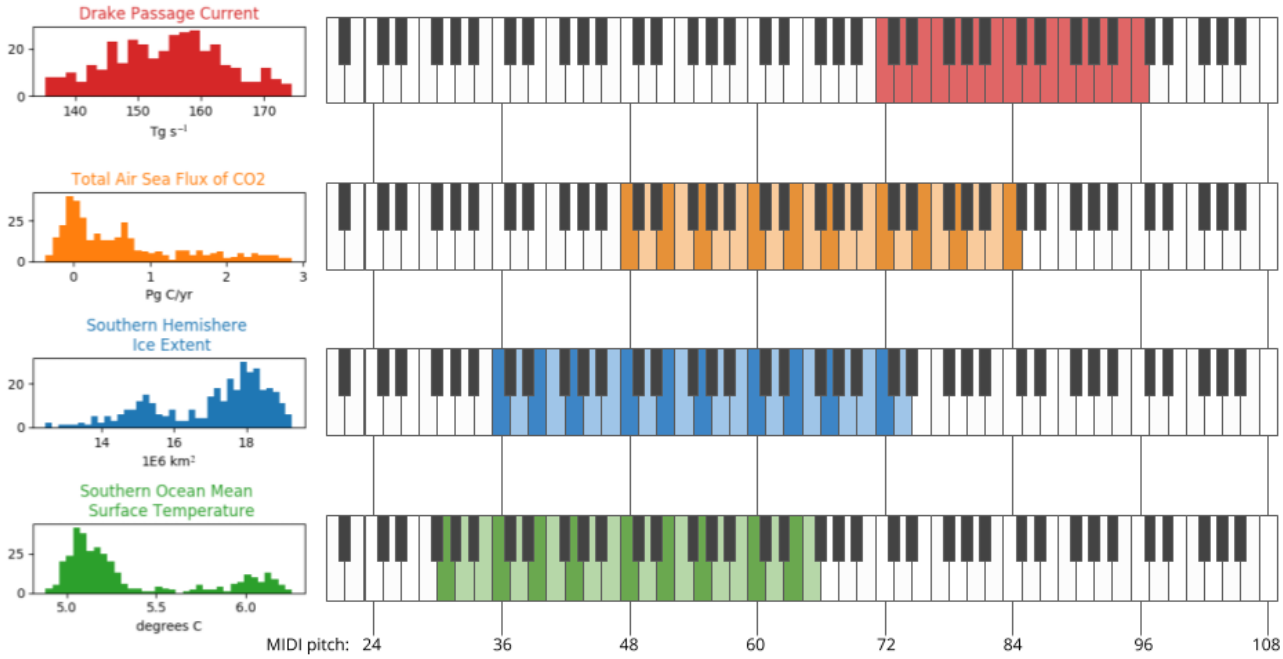
Line 119 also says "each model dataset is linked to a series of notes", so does this mean each note is a data point? Again, translating this into climate data would be helpful. Similar suggestions for Fig 2 (see below) and lines 169-172. Also, many of the comments shown in the next few pages are related to this issue.

LdM: In addition to adding the new keyboard figure (see below), I've changed this entire paragraph to:

> Each model timeseries dataset is converted into a series of consecutive MIDI notes, which 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 is 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 highest and lowest pitched notes. The lowest and highest notes available for each track are pre-defined in the piece's settings. Each track is given its own customised pitch range, so that the tracks may be lower pitch, higher pitch or have overlapping pitch ranges relative to other tracks in the piece. The ranges of notes available for the piece \textit{Earth System Allegro} is shown in fig.~\ref{fig:histograms}. 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 shows a standard piano keyboard which 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.

Figure 2- It would be very helpful if you can connect what you show in the piano keyboard to climate data. See figure 1 of George et al. (2017, American Meteorological Sociey) for example. Again what does each note represent? What does each pitch represent? A bit hard to follow as a non-musician.

LdM: Based on the 2017 paper in the Bulletin of the American Meteorological Society by St George et al (*https://doi.org/10.1175/BAMS-D-15-00223.1*) I've added the following image and caption to this paper:



Caption:

> 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, but the lighter coloured keys show the other notes which are available. Note that both the C major scale and chord do not include any of the ebony keys on a piano, but these notes would be used if they are within the available range.

Below, my comments are shown line by line:

Line 23 (Introduction)-The authors introduce the topic well, and the references they list are relevant and helpful. Since this study combines sonification with imagery, it would also be helpful to know if this approach has been taken before, and if so, how does this study contribute (or build on) previous work?

LdM: Added the following text.

> 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.

Line 56 points out the potential for biased-interpretation of data using sonification. However, the authors do not return to this issue later to discuss it. Was this a concern during this study and how was it addressed?

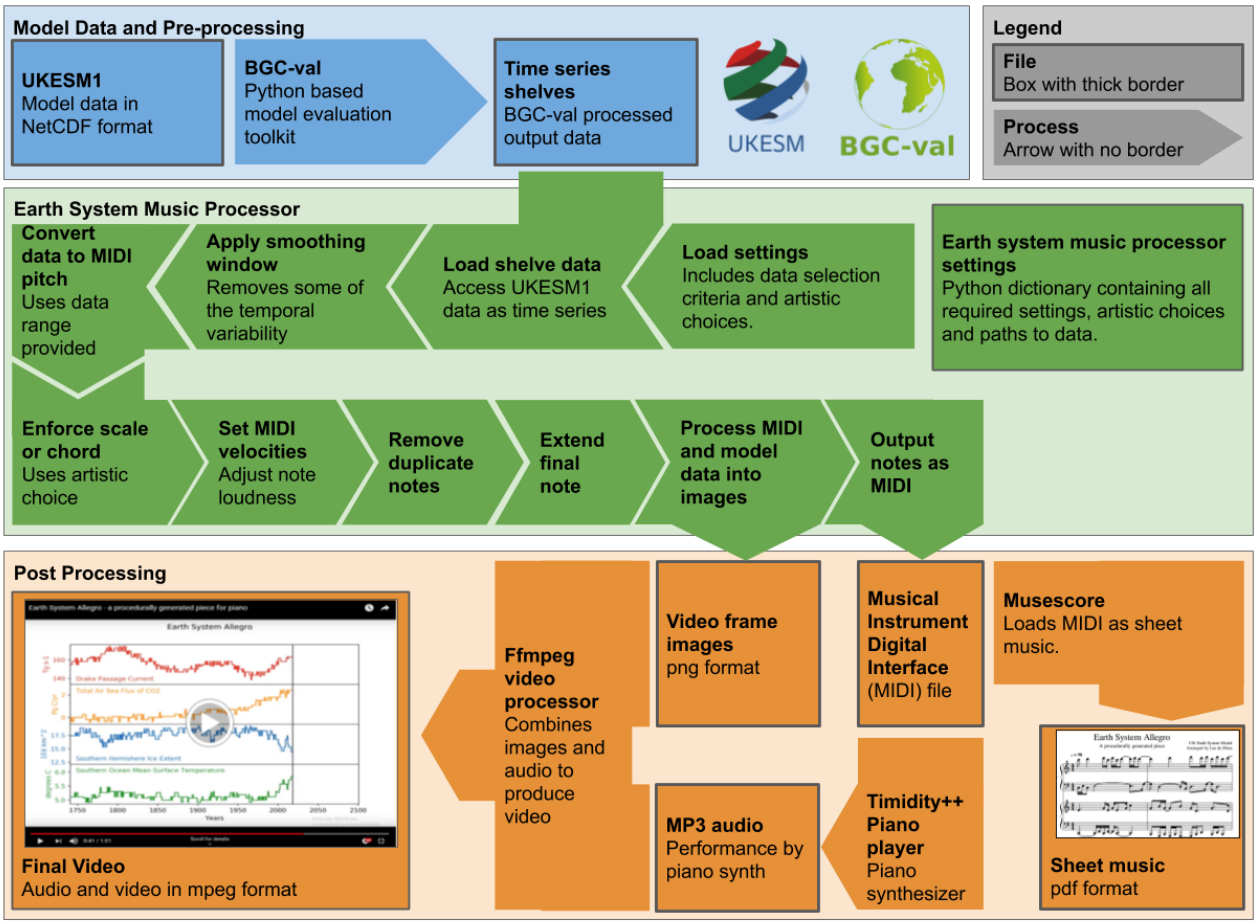
LdM: Upon reflection, we never wanted the musical pieces to be a neutral objective version of the data. We always wanted to try to communicate some of the emotional context of the data.

Re-wrote this paragraph to be:

> In addition to its practical applications, sonification is a unique field where scientific and artistic purposes may coexist \citep{Tsuchiya2015}. This is especially true when in addition to being converted into sound, the data is also converted into music. This branch of sonification is called musification. Through the choice of musical scales and chords, tempo, timbre and volume dynamics, the composer adds 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 a true objective representation of the data. Note that the philosophical distinction between sound and music is beyond the scope of this work. Furthermore, even though the composer may have made musical and artistic decisions to link the behaviour of the data with an emotive state, it may not necessarily be interpreted in the same way by the listener.

Figure 1. Though flow charts are generally produced in this way, I suggest to add a few images (one per section) to draw in the readers. The sections are: datasets (top), music (middle) and videos (bottom).

LdM: We have reworked the methods plot now. It should be both clearer, more colourful and include a few images.



The new caption reads:

> 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 MIDI data, and orange area show the post processes stages which convert images and MIDI into sheet music and video.

Line 224. When you state “The Earth System Allegro is a relatively fast-paced piece in C Major”, can you describe what C Major sounds like for non-musicians? Also the rest of the sentence starting with “. . .showing some important metrics of the happy to keep. . .” does not make grammatical sense. Please revise.

LdM: Changed this paragraph to:

> 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 SSP1 1.9. This is the future scenario in which the anthropogenic impact on the climate is at a minimum. 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." As this was the first piece in the series, the link between this seemed an appropriate way to start the Earth System Music project. 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.

Line 226. Could you explain how this video demonstrates the principles of sonification using the data series?

LdM: Changed this phrase to:

introduce the principles of musification of UKESM1 time series data.

This was the first piece in the series and does introduce the core-concept of the project, that the music follows the data.

Line 232. I think there may be a typo here. Could it be “year 2030/2040” as oppose to year 2100?

LdM: Changed this phrase to:

Even under SSP1 1.9, UKESM1 predicts that this value would rise from around zero during the pre-industrial period to 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.

Line 235. Consider deleting this sentence as it is repetitive.

LdM: removed and replaced with:

The fourth field is the Southern Ocean mean surface temperature, shown in green, which slightly rises from approximately 5 degrees in the pre-industrial period up to a maximum of 6 degrees.

Line 240. Consider deleting the sentence starting with “Effectively, . . .” It is redundant.

LdM: Removed.

Line 248. Change “there’s” to “there is”, and “doesn’t” to “does not” in line 292. And reflect this change throughout the manuscript.

LdM: Done

Line 250. Again “a very common 4 chord song: C Major, G Major, A Minor, and F Major” does not mean anything to a non-musician. Please clarify this by giving an example for each or give a word to describe what they sound like.

LdM: Added the sentence which should add some context.

> This chord progression is strikingly popular and may be hear 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 Jazon Mraz, amoung many others.

This is a bit of a trick, as some of these songs are the same chord progression in a different key (For instance, Africa by Toto is written in A Major). I fear that adding the complexity of the roman numeral notation is a step too far for this work! Out of interest, the following songs are written using this progression:
https://en.wikipedia.org/wiki/List_of_songs_containing_the_I%E2%80%93V%E2%80%93vi%E2%80%93IV_progression

Lines 250-253. Draft a similar paragraph for section 3.1.1. This helps connect the music structure with what the dataset represents.

LdM: Done, see above.

Line 256. Add a reference to Figure 3, pane 3, at the end of this sentence.

LdM: Done

Lines 257-259. Add the name of scenarios (e.g., SSP5 8.5) to Figure 3, pane 3.

LdM: I’m not able to do this, these figures show the final frame of each video, not the data itself. As the video is already published, it’s not possible to do this. The colour code is described in the text in lines 255-260.

Line 270. Add reference to Figure 3, pane 4, after “E minor”.

LdM: added the sentence:

> The final frame of this video is shown in pane 4 of fig. 3.

Line 273. How are these 15 historical simulations are shown in the figure? Only 6 lines are shown. Have they been grouped?

LdM: As mentioned above, figure 3 only shows the final frame of the videos. I’ve changed figure 3’s caption to be clearer:

> Figure 3: 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 x-axes which changes over the course of the video. This means that panes 2 and 4 show only a small part of time range.

Line 274. “This piece uses a repeating 12 bar blues structure in E minor”, what does this mean to a non-musician, and how is this connected to the dataset it is reflecting?

LdM: Added the following paragraph to make the point clear about the choice of a 12 bar blues.

> This piece uses a repeating 12 bar blues structure in E minor and a relatively fast tempo. This chord progression is was exceptionally common progression, especially in the blues, Jazz and early rock n roll sounds. 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 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.

Line 285. What initial conditions are the authors referring to?

LdM: Changed the text to

> 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.

Line 286. When you state “. . .the results of our projections are due to changes. . .” what changes are the authors referring to?

LdM: see above

Line 294. Please give an example of what it is meant by “inherent change” and “underlying drift”.

LdM: I’ve re-written this paragraph for greater clarity and this should address most of the issues raised in this section.

> This piece combines the spin up of the United Kingdom Earth System Model with the chord progression of John Coltrane's Giant Steps. 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 CO2

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 trend 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 were met , Yool 2020.

Line 295. The spin up ran for 5000 simulated years. Why 5000 years? How was this time selected? A reference is provided, but it would be useful to add a sentence explaining why.

LdM: I've added more details on the spin up criteria, please see above. Also note that the UKESM spin up paper has recently been submitted to JAMES after review and is expected to be accepted for final publication before this paper. A suitable reference will be added when it is available.

Line 305. It may be useful to label these lines in Figure 3, pane 5 or describe them in the caption.

LdM: These lines do appear in figure 3, pane 5, I've added the following text to the caption.

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.

Line 311. Why was the musical progression slowed to one chord per four beats? What does it mean in terms of the climate dataset?

LdM: To be honest, this was a happy accident due to a bug in the original code. The original version at full speed just sounded too chaotic. Changed the text to:

This change occurred as an accident, but we found that the full speed version sounded very chaotic, so the slowed version was published instead.

Line 335. Decapitalize "Global total ice" and insert a space between "extent" and "blue".

LdM: Done

Line 365. Change "view" to "video" in "the percentage of the view that the average audience viewed".

LdM: Done

Line 366-369. Consider deleting this part starting from “Aside from the metrics. . .” These numbers are too small to be meaningful, and are not discussed.

LdM: The first reviewer had a stronger interest in metrics beyond the youtube statistics. We have moved this part into that section and extended the discussion to include these metrics.

Lines 370-378. Consider deleting the whole paragraph or move to discussion.

LdM: Moved to discussion.

Figure 7. Consider removing it from the manuscript, but keep the text (lines 387 onward). The figure does not add much to the manuscript, especially when half of the data is unknown.

LdM: Figure removed but kept the text.

Lines 390-392. Consider deleting this or move to discussion.

LdM: Split this paragraph into two and put second half in the discussion.

Line 406. The study goals stated here differ from those stated in page 10. Please keep the goals consistent.

LdM: Fixed.

Line 411. The authors conclude that once the concept was demonstrated, there was reduced enthusiasm from the audience to return to it. How do they know that? Another possibility could be that the audience didn’t feel the need to return to it, or it could also be that the videos sparked their interest further so that they ended up checking out similar videos outside the playlist. These are all possibilities, and there is no evidence for or against them. I suggest sticking to the facts, and only interpret the data when it is actually possible (which is not the case here).

LdM: Removed this sentence.

Line 412. The last sentence may be true but it is irrelevant to this paragraph. Was the goal to grow a YouTube channel? Why do the authors mention this here?

LdM: Removed this sentence

Lines 420-426. The sea surface temperature aria is also the most visually simple animation when compared with the rest. The viewer is not required to keep track of multiple datasets and listen to the music at the same time. Could this be also why this piece has the highest audience retention?

LdM: added:

> The sea surface temperature aria is also the most visually simple animation of the six pieces. Only one pane is visible in the video and much of the piece only includes one or two voices at a time. It may be possible that this simplicity holds the audience's attention.

Line 430. There is no documented evidence that the music pieces and animations improved the wider public's understanding of climate change modelling. The authors mention this in the next paragraph. So I suggest to delete the "perhaps, improve the wider public's understanding of climate change modelling". One could hope for that, but this study was not designed to assess that, and certainly did not do that.

LdM: Changed text to:

> While we hoped to improve the wider public's understanding of the methods used in climate change modelling, the tools available to us within YouTube studio do not allow any way of assessing this. Please see the Limitations and Future Work section, below.

I suggest to move some of the content currently placed in the discussion section to two new sections: Limitations and Future Work. This means most of what is shown in page 19-20 can be reorganized to fit into one of these two sections. This might help the readers.

LdM: Created this section and reorganised the discussion into two parts.

Line 439. Here the authors suggest hosting live events to fully explain the methodology used by the modelling community. But is this something non-experts are interested in, or is this the aim of this study? I thought the idea was to use a unique communication method (sonification and imagery) to explain complex datasets to nonexperts. If this method requires a live event for further explanation, then it does not fulfill what it was supposed to do: to engage non-experts.

LdM: At the moment, the videos by themselves do not even attempt to include an explanation of the methods used in Earth System Modelling. All explanation was in the video description below the video. However, the point of this paragraph is confused by the addition of a sentence about a live performance, so it was removed.

We changed this paragraph to:

> The videos themselves 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 YouTube studio, it is not currently possible to determine whether the viewers have expanded, read or understood the description. 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.

Line 462. The authors state that it was hard to distinguish the different datasets in the music. One solution would be to insert a very short silence in music between different datasets. Just an idea.

LdM: The confusion here is that one sentence is trying to cover two ideas. We changed this sentence to:

> 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 within in a given piece was performed by the same instrument, making it difficult to distinguish the different datasets being performed simultaneously.

Line 504. Insert a space between the word viral and the references.

LdM: done

Line 510. Insert a space between the word afternoons and the references.

LdM: done

Line 514. “they reached an audience of 251 unique viewers and a total view count of 553”

LdM: done

Table 1. Add unit of time for “duration”. Minutes?

LdM: done

Dr. Lee de Mora
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Prospect Place
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PL1 3DH

Dear Geoscientific Communication editors, referees and reviewers,

We received two review comments and one short comment. We have addressed their comments in this document, and made changes to the main document, also attached. We're like to thank both anonymous referees and the short comment author for their helpful comments. Thanks to their contributions, this work is in a much better state and should be easier to follow.

For clarity, we will reproduce the comments and respond to them in turn. Our responses are marked in bold and begin with **"LdM:".** The new text are included with an indent and may include some latex grammar. Alternatively, a document showing the difference between the old and the new version is also available.

Sincerely,

Lee de Mora – representing the authorship team.

Short Comment: Paul Pukite

We have also received the following comment from Paul Pukite:

> In my years following scientific research, I have no idea what the meaning of this is https://www.youtube.com/watch?v=RxBhLNPH8ls Music appreciation is subjective, but scientific research results should not be. Sorry if I don't get what the point is.

Paul has also added a comment on the youtube channel, and we have been communicating with him directly there. We wrote:

> The idea here is to use music to draw people in, then they learn about how Earth System Modelling works. This piece was the first one in a series of six, and the main idea here is just to show how the musification process works. Ie, we take Earth System Model data and turn it into music.
>
> The next piece in the series introduces the concept of a control run. Then the following piece shows how future scenarios work in the context of global warming, then there's a piece about ocean acidification and how historical runs branch from the pre-industrial control run. There's also a piece about how the model is spun up, and another about the 7 SSP scenarios in CMIP6. These are all key concepts in climate modelling, but might not known outside our community. The goal isn't really to use the data to identify new behaviours in the model, but to show how we make models in a (hopefully) fun way.
>
> Happy to answer more questions if you have any!

Earth System Music: the methodology and reach of music generated from the United Kingdom Earth System Model (UKESM1)

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Abstract.

Scientific data is almost always represented graphically ~~either~~ in figures or in videos. With the ever-growing interest from the general public towards understanding climate ~~science~~sciences, it is becoming increasingly important that ~~we~~ scientists present this information in ways ~~accessible~~ 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~~and use them to test whether we can use music to engage with the wider community.~~ . Each of these pieces ~~is based around a unique part of~~ presents a unique aspect of the ocean component of the UKESM1~~'s ocean component model~~, 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 ~~performed by the~~ created in the Musical Instrument Digital Interface (MIDI) format and then performed by a digital piano synthesizer~~, TiMidity++, and were published on the lead author's YouTube channel. The videos all show the time progression~~ . An associated video showing the time development of the data in time with the music ~~and a~~ was also created. The music and video were published on the lead author's YouTube channel. A brief description of the methodology ~~is posted below~~ was also posted alongside the video. To ~~disseminate~~ begin the dissemination of these works, a link to each piece was published ~~on~~ using the lead authors personal and professional social media accounts.

The reach of these works was analysed using YouTube's channel monitoring toolkit for content creators, YouTube studio. In the first ninety days after the first video was published, the six pieces reached at least 251 unique viewers, and have 553 total views. We found that most of the views occurred in the fourteen days immediately after each video was published. ~~In effect, once the concept had been demonstrated to an audience, there was reduced enthusiasm from that audience to return to it immediately. This suggests that to use music effectively as an science outreach tool, the works needs to reach new audiences~~

~~or new and unique content needs to be delivered to a returning audience~~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 (**?**). 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 (**?**). Sonification also ~~allow~~ allows several metrics to be displayed simultaneously using variations in pitch, timbre, volume and period (**??**). For these reasons, sonification is widely used in medicine for monitoring crucial metrics of patient health (**???**).

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, (**?**) 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*, (**?**) 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 (**?**) and (**?**) 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 (**?**). 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.

~~With the ever-growing interest from the general public towards understanding climate science, it is becoming increasingly important that we present this information in ways accessible to non-experts. When accompanying an animated visualisation, as performed in this work, the combination of music and imagery provides additional contextual clues to aid in the interpretation.~~

In addition to its practical applications, sonification is a unique field where scientific and artistic purposes may coexist (**?**). This is especially true when in addition to being converted into sound, the data is 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 adds emotive meaning to the piece. As such, ~~sonification~~ unlike sonification, musification should be treated as a potentially biased-interpretation of the underlying data. It can not be 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 an emotive state, it may not necessarily be interpreted in the same way by the listener. ~~There is a fine line between a scientific presentation of data and an emotive interpretation of the same data; sonification allow pieces to sit on either side of the line.~~

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. It is also becomingly increasingly easier for scientists to use tools such as social media to engage with non-expert audiences and the wider public.

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) (**?**). By using simulated data instead of observational data, we can reach time periods beyond 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. 3.1.

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 and shared via the ~~authors~~ author's personal and professional social media network.

In addition to hosting the video, YouTube also provides YouTube studio, a powerful channel monitoring toolkit for content creators (**?**). This toolkit allows content creators to monitor the reach, engagement and audience demographics (age, gender, country of origin) for their channel as a whole, as well as for individual videos. This work includes a study on the reach of

these pieces using these tools. Section 3.2 contains a brief summary of the methods used to measure the reach~~, and the results~~ . The results of this analysis are shown in sec. 4, and a discussion is in sec. 5. It should be noted that this work is an early pilot study and the limitations of this approach are outlined in sect. 6.

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) (**?**). 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 (**?**), the Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification (MEDUSA) is the sub model of the marine biogeochemistry (**?**) and CICE simulates the growth, melt and movement of sea ice (**?**).

The UKESM1 is being used in the UK's contribution to the sixth international coupled model intercomparison project (CMIP6) (**?**). The UKESM1 simulations that were submitted to the CMIP6 were used to generate the musical pieces. These simulations include the pre-industrial control (piControl), 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 (**?**).

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 is 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/.

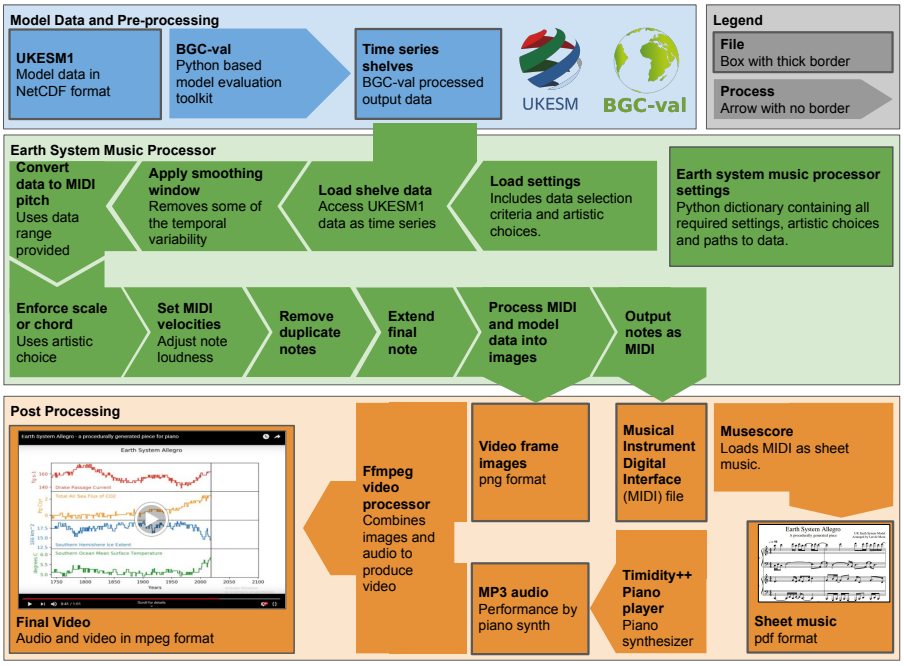

Figure 1. The computational process used to convert UKESM1 data into a musical piece and associated video. The ~~sharp cornered~~ boxes with a dark border represent files and datasets, ~~where as~~ and the ~~rounded cornered boxes~~ arrows and chevrons represent ~~a process~~processes. The ~~light~~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

The time series data is calculated from the UKESM1 data by the BGC-val model evaluation suite (**?**). 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 ~~play~~ perform a piece of music (**?**). All six pieces shown here are ~~composed of several MIDI~~ 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 ~~third~~ 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 ~~be~~ become unpleasant when performed by TiMidity; other MIDI pianos may have more success. ~~MIDI~~ Also note that MIDI's 127 note system 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~~

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 ~~dataset is linked to~~ timeseries dataset is converted into a series of consecutive MIDI notes, which 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 is 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 ~~highest and lowest~~ 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 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 shows a standard piano keyboard which 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:

$$C_{maj_0} = \{0, 4, 7\} \tag{1}$$

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

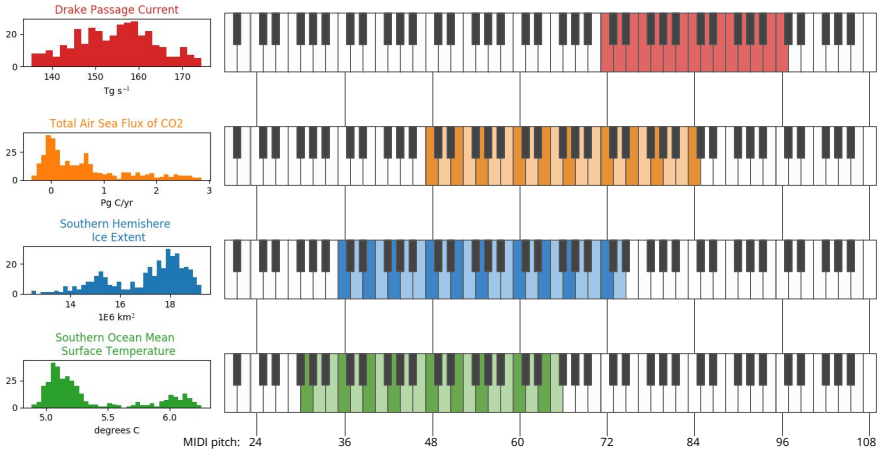

Figure 2. The musical range of each of the datasets used in the *Earth System Allegro*. The four histograms on the left hand side show the distributions of data used in the piece, and the right hand side shows a standard piano keyboard which the musical range available to each dataset. In this piece, 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.

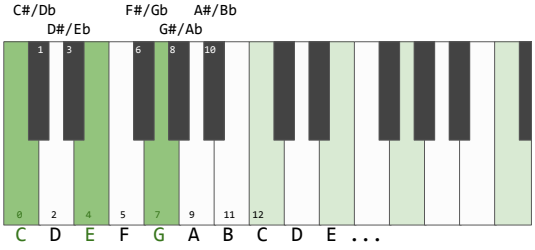

Figure 3. A depiction of a standard piano keyboard, showing the names of the notes, the number of these notes in MIDI format. The C major chord is highlighted in green, and the zeroth octave is shown in a darker green than the subsequent octaves.

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:

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

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

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

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:

$$C_{min_0} = \{0,3,7\}$$
$$C^7_{maj_0} = \{0,4,7,11\}$$
$$C^7_{min_0} = \{0,3,7,10\}$$
$$\ldots$$

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 **?** or **?**.

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 ~~in two stages~~using the following method. First, the data is translated into the pitch scale, but kept as a rational number between ~~0 and 127.~~ 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. ~~The~~ As mentioned earlier, the pitch of the MIDI notes ~~need to~~ 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 is 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.

~~While the method is relatively straightforward and repeatable, 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.~~

After applying this method to multiple tracks, they are saved together in a single MIDI file using the python MIDITime library, (**?**) Having created the MIDI file, the piece is performed by the TiMidity++ digital piano, (**?**), 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, (**?**). 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.

While the method is relatively straightforward and repeatable, 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 ~~'re~~ 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, (**?**)~~.~~ , 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, (**?**). The videos were published in an ad hoc manor, as they were available. Each new video was shared via the ~~authors~~ lead author's personal social media accounts, twitter, Facebook, WhatsApp and the initial playlist was shared on the ~~data is beautiful sub-reddit~~*data is beautiful* reddit page, (**?**). and the piano reddit page (**?**). The videos were also shown at several scientific meetings, notably to an audience of approximately 100 scientists at the National Centre for Earth Observation Annual Conference in September 2019.

3.1 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

The main goals of the work were to generate music using climate model data, to use music to illustrate some standard practices in Earth System modelling that might not be widely known outside our community, and to quantify the early dissemination of these pieces. 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*~~, and to highlight~~ . 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~~in the *Pre-industrial Vivace*. The~~ . The *Sea* ~~*surface temperature aria*~~*Surface Temperature Aria*'s goal was to demonstrate the range of ~~differences between the various future projections, and~~ behaviours of the future climate projections. *Ocean Acidification in E minor* aimed to show the impact of rising atmospheric CO_2 on ocean acidification

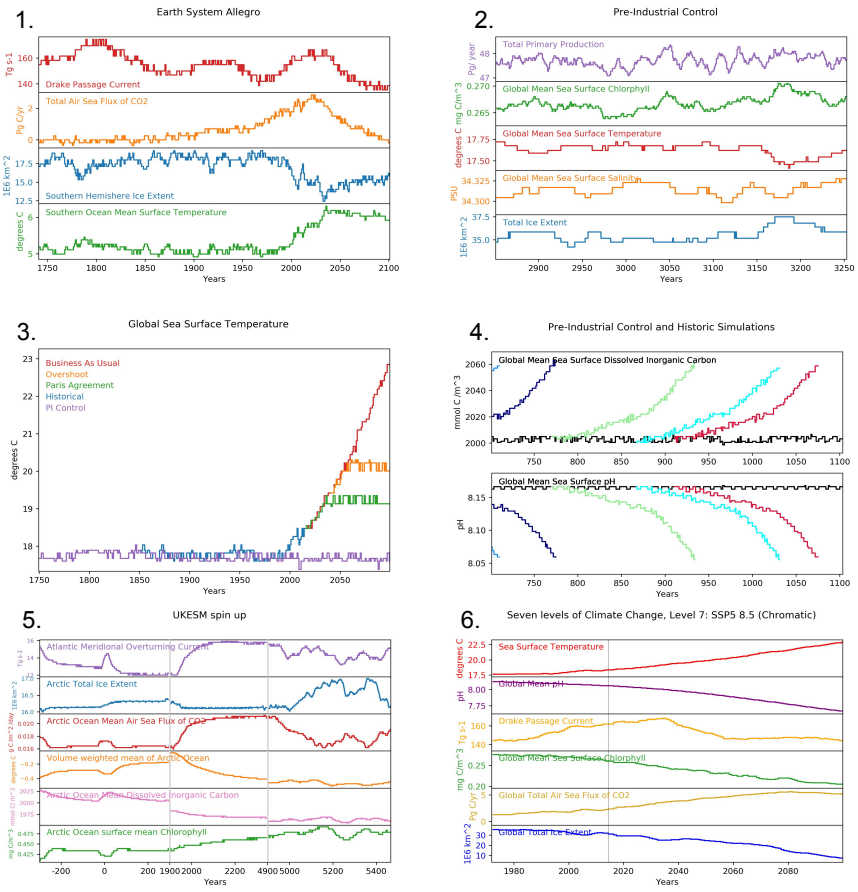

Figure 4. The final frame of each of the six ~~video~~videos. These ~~figures~~ frames of the videos are shown in the order that they were published. The videos 1), 3), 5) and 6) use a consistent x-axis for the duration of the video, but videos 2) and 4) have rolling x-axes ~~which changes~~ that change 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.

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~~ocean model~~, 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 ~~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.

3.1.1 Earth System Allegro

The *Earth System Allegro* is a relatively fast-paced piece in C Major, showing some important metrics of the ~~happy to keep it there of the~~ Southern Ocean in the recent past and projected into the future with the SSP1 1.9. ~~This is~~ The SSP1 1.9 projection is is the future scenario in which the anthropogenic impact on the climate is ~~at a minimum~~the smallest. ~~This video~~ 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." As this was the first ~~of the seriesand aims to demonstrate the principles of sonification using~~ piece in the series, this seemed an appropriate way to start the Earth System Music project. 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~~ Passage current, shown in red in the top left pane of figure 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 ~~close to~~ a maximum of approximately 2 ~~petagrams~~ Pg of carbon per year ~~by the year 2100.~~ 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~~. This is the average surface temperature of the Southern Ocean.~~ , 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 module 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.

3.1.2 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 ~~(approximately 1400 years)~~ simulation of the

Earth's climate without the impact of the industrial revolution or any of the subsequent human impact on climate. ~~Effectively, it is a simulation of a pristine natural environment with no human influence~~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 ~~anthropocentric~~ anthropogenic impact.

The final frame of the ~~Pre-industrial Vivace~~ *Pre-industrial Vivace* video is shown in the top right pane of figure 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 ~~'s~~ is no long term trend in any of these fields. However, there is significant natural variability operating at decadal and millennial scales.

~~The chord progression may sound familiar as it is a very common 4 chord song:~~ 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 chords formed from notes of the C major scale~~and a familiar chord progression in a major key, this piece aims to ~~create an emotional connection between the model output and the sonification of the data~~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 ~~simulation~~ environment which is free running and uninhibited by anthropogenic pollution.

3.1.3 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 three scenarios are 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 ~~temperament~~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 chord progression. ~~It~~ 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 ~~when looking towards the~~ as the piece progresses to the catastrophic SSP5 8.5 scenario at the end of the 21^{st} century.

3.1.4 Ocean acidification in E minor

Ocean acidification in E minor demonstrates the ~~branching of~~ 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 is shown as a black line and the coloured lines represent the fifteen historical simulations.

This piece uses a repeating ~~12 bar blues~~ *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 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 (**??**). The atmospheric CO_2 is absorbed from the air into the surface ocean, 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 ~~starting points~~ 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.

3.1.5 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*, (**?**). The spin up is the process of running the model from a set of initial condition to an equilibrium steady state. When a model ~~runs in~~ reaches a steady state, this means that there is no ~~underlying~~ significant trend or drift in the mean behaviour ~~.~~ of several key metrics. For instance, as part of the C4MIP protocol, **?** 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. ~~While a steady state model doesn't have any significant long term trends or drifts; it can still have short term variability.~~

The spin up is a crucial part of model development~~because without it, we would not be able to say whether any trends observed~~ . 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 ~~would be due to inherent change or underlying drift.~~ 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 were met (**?**). (**?**).

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~~ 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.

3.1.6 Seven Levels of Climate Change

This piece is based on a YouTube video by Adam Neely, called The 7 Levels of Jazz Harmony, (**?**). 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 ~~levels~~ 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 and 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 ~~is~~ 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~~ Passage current (yellow), the global mean surface chlorophyll concentration (green), the global total air to sea flux to CO_2 (gold) and the ~~Global~~ global total ice extent (blue). As the piece progresses through the seven levels, the ~~behaviour~~ anthropogenic climate change of the model becomes more extreme, matching the increasingly esoteric harmonies of the music.

3.2 Quantification of reach

YouTube's built-in toolkit for channel monitoring, YouTube studio, was used quantify the reach, engagement and audience for the individual videos, as well as the entire channel (**?**). Using these tools, we have investigated the first 90 days that the videos were published, starting from the 21^{st} of August 2019 to the 18^{th} of November. ~~There are two reasons for this choice. Firstly, most of the views occurred immediately within the first few days after the videos were published, so later time periods do not have as much influence on the overall reach. Secondly,~~ This is because YouTube studio can only produce reliable data on unique viewers for a period up to 90 days. Unique viewers are an estimate of the total number of people to watch a video. This metric accounts for when a single person watches a video on multiple devices or several times on the same device. It also accounts for when multiple people share the same device using separate YouTube accounts.

In contrast to the unique viewers metric, the view count metric includes views from viewers who re-watch the same video multiple times. Of course, neither unique viewers or view count can account for the audience size if multiple people watch a video at the same time on the same screen or if the video is shown to larger audiences.

Using YouTube studio, it is also possible to retrieve some basic demographic information about the viewers: where they are in the world, their gender, age and how they came across the video (traffic source). However, this channel has too few views to get information about gender and age, so we are limited to geography and traffic source.

These videos were published as they were ready and shared in an ad hoc way via the lead author's personal Facebook, twitter, WhatsApp and reddit social media networks. The sharing posts included a link to the new video, and a brief comment on the contents of the video. Each video was posted alongside a brief description and used the three main tags: #Music, #Science and #ClimateChange, as well as several ~~others~~other minor hashtags. Each piece was also added to a YouTube playlist, which ~~has also been shared~~ was shared via social media in the same way as the individual pieces. The playlist lists the pieces in the order that they were published. ~~There was no particular timed-release~~As this was a pilot study, there were no particular timed-releases, no press release and no direct assistance from the PML, NERC or UKESM communications teams. The videos were then disseminated through these networks and allowed to reach wider audiences. ~~No~~ In addition, no paid advertisements were ~~made.~~

purchased. There is very little publicly available data about the individuals who have shared these videos within private networks such as Facebook or WhatsApp. Furthermore, it ~~'s~~ is not possible to know how many people viewed their posts. For this reason, this work focuses on the data made available to content creators in YouTube studio. Please see sect. 6 for a discussion on possible extensions to this pilot study where these avenues could be explored.

4 Results

Table 2 shows a summary of the reach of these videos including the number of unique viewers, the total number of views, the average view duration, the average audience retention and the cumulative watch time for each of the six videos and a total. The number of unique viewers is approximately half of the total number of viewers which suggests that many viewers watched the videos several times. The average view duration indicates how long the viewers watched the video and the average audience

retention is the percentage of the ~~view~~ video that the average audience member viewed. ~~Aside from the metrics shown in tab. 2, YouTube studio provides a few other metrics of channel behaviour. For instance, during this time period, the number of channel subscribers rose from 1 to 10, and 8% of the view time came from subscribers. The 6 videos received a total of two comments, ten likes and zero dislikes.~~

~~As a comparison, the UKESM1 short video introduction, , video was published on the 1st of November 2017 and has received 183 views and zero likes or dislikes in the first two years since it was published. This is the only other video about UKESM1 on YouTube, and the Earth System Music playlist has received three times the total views. By itself, the Earth System Allegro video received more views in the first fortnight than the short introduction video received in two years. The YouTube video about Earth System Models with the largest viewership, E3SM: DOE's New, State-of-the-Science Earth System Model, , has received 4479 views after 18 months online. On the other hand, the NERC science YouTube channel has more than 700 subscribers at the time of submission, the most popular video *Anatomy of an earthquake - Professor Iain Stewart* has 82K views, (?). Both these videos have received significantly more views than the Earth System playlist.~~

The cumulative number of unique viewers for each of the six videos over the first 90 days of the project is shown in fig. 5, and fig. 6 shows the cumulative non-unique view count for each video. The x axis of these figures has been zeroed such that the day that the first video was released (21/08/2019) is day zero. These figures both show that the keenest interest in the videos was at the beginning of the project, when three videos were published in quick succession. The later three videos did not receive the same number of views. After the initial period of high interest, nearly all videos have a similar viewing rate, approximately 5 views per month. Figure 7 shows the total number of views on the day that each video was published. It is worth noting that the first two videos were both published on the same day. The ~~Earth System Allegro~~ *Earth System Allegro* had the highest opening day view count, and the ~~Sea Surface temperature~~ *Sea Surface Temperature Aria* video had the lowest opening day view count.

~~Figure ?? shows~~ YouTube studio also provides the geographic distribution of part of the viewership, based on the IP address of the viewer. The origin of more than half of the viewership is unknown due to the restriction that content creators may only see demographics data for a subset of viewers. Outside of the viewers of unknown origin (56.6%), the United Kingdom dominates the list with 32.5%, followed by the United States ~~, France and Germany. This work originates in the United Kingdom and uses data from the United Kingdom Earth System Model, so it is not surprising that the United Kingdom is the largest source of viewers. It is likely that these works have been viewed outside those four countries, however no data is provided for 56.5%of the views~~(6.5%), France (2.2%) and Germany (2.2%).

~~The geographic distribution of the viewers of these videos.~~

Figure 8 shows the source of the total views for this channel divided into categories. The traffic sources are external: traffic from websites and apps that have the embedded or linked the video; playlist: traffic from any playlist that included one of the videos; playlist page: traffic from the Earth System music playlist page; channel page: traffic from the YouTube channel page; direct: external traffic from direct URL entry; YouTube search: traffic from the YouTube search engine; other YouTube: traffic from other places in YouTube, for instance from subscribers and notifications; browse features: traffic from the home

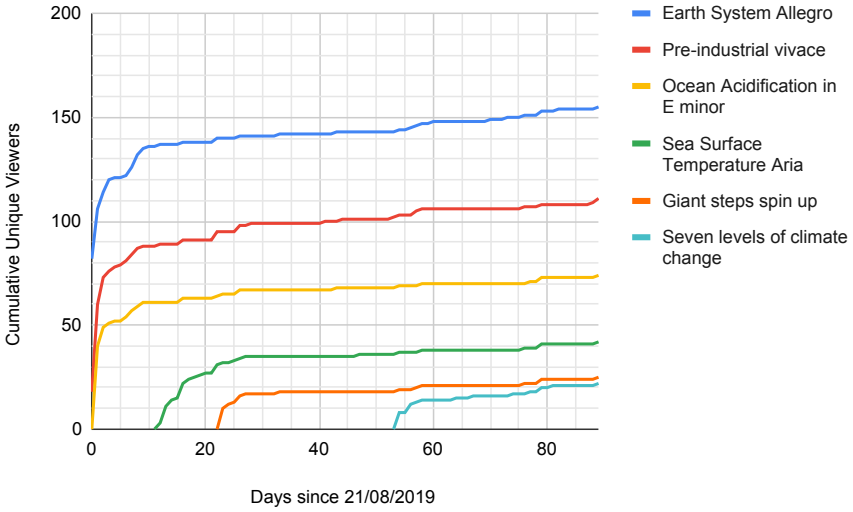

Figure 5. The cumulative number of unique viewers of each video over the 90 day period starting from the publication of the first videos.

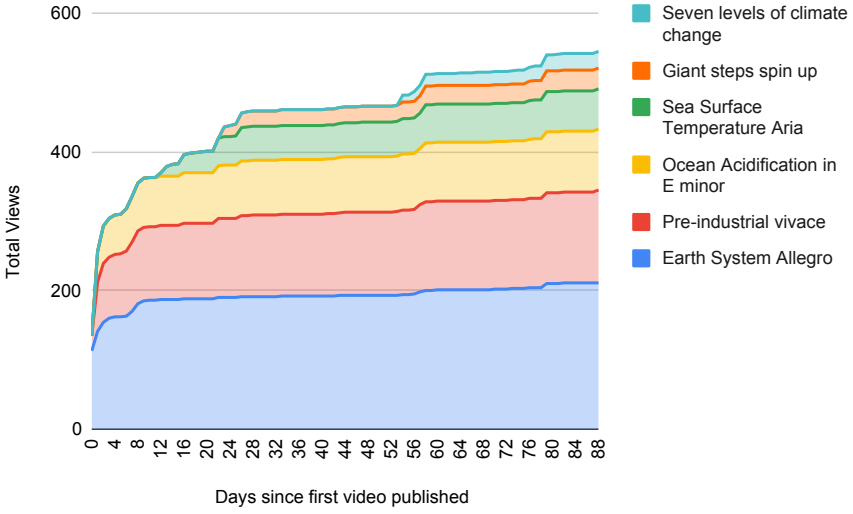

Figure 6. The total cumulative non-unique view count of each video over the 90 day period starting with the publication of the first video.

screen, subscription feed, watch later and other browsing features; and finally, suggested videos: traffic from the suggestions that appear next to or after other YouTube videos.

This figures clearly shows that the largest source of the traffic is from External sources, which is likely to be from people watching the videos on social media such as Facebook, Twitter or reddit. Using YouTube studio, it is not possible to further

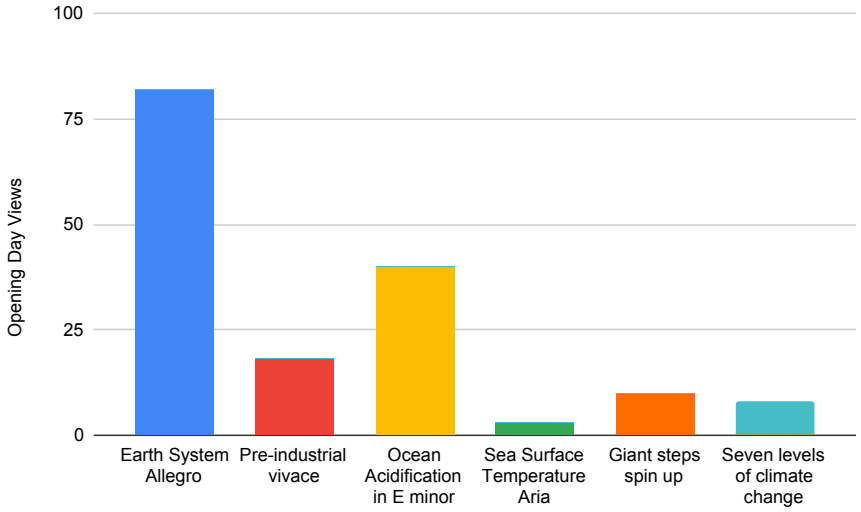

Figure 7. The total view count of each video on the day that it was published.

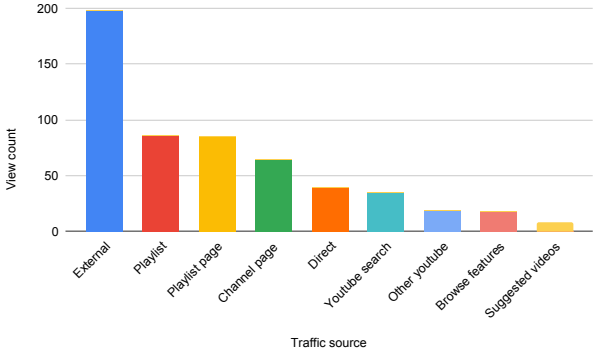

Figure 8. The traffic source the views of these videos. This figure shows how viewers came to watch these videos.

differentiate which external source led to the view. The second largest single source of traffic is the playlist, which means that many viewers watched several videos in a row from the playlist. There is relatively little traffic from within YouTube in the suggested videos and browse features traffic sources. This suggests that most of the views come from people within the lead author's social media network, and that YouTube has not included these videos in suggestions to a wider audience.

Aside from the metrics shown in tab. 2, YouTube studio provides a few other metrics of channel behaviour. For instance, during this time period, the number of channel subscribers rose from 1 to 10, and 8% of the view time came from subscribers. The 6 videos received a total of two comments, ten likes and zero dislikes on YouTube.

The following statement were posted via social media. These were posted directly on the YouTube video page, or on social media posts linking to the video via facebook, twitter and reddit. Note that I have removed emojis and gifs, but otherwise reproduced comments as they originally appeared.

1. This one was very dramatic.
2. It gets quite dramatic after 1950-60
3. This was submitted as a scientific research paper here, but don't understand what the point is.
4. Wow! That's awesome!
5. Great idea
6. That's Crazy!!
7. Awesome! Personally I was hoping to hear something of the same ilk as system of a down or similar. Does make modelling sound far more upbeat though
8. Brilliant idea! Just like Herman Hess's book 'The Glass bead Game', where data is unified from many sources and brought together by many senses. Listen to how the ocean sings!
9. AMAZING!!!!
10. A total new meaning for the "listen to the ocean" motto
11. That's awesome! Can you post this to someone with a bigass twitter handle. This deserves more attention. Maybe send it to Adam Rutherford at Inside Science?
12. It's quite different from the previous one! Super Cool stuff!!
13. This is amazing. If you can find a setup that would cause noticeable change in the music between pre-industrial and future you're viral
14. I love this!! Well done!
15. This is amazing ! Was initially quite surprised that these weren't more tonally chaotic - then I read I the blurb for the top video. I presume that you could do the same with any choice of key and scale? Also, I hope you realise that, with your choice of C-major, you have made something worthy on inclusion in the next Axis of Awesome medley
16. Certainly very interesting, but it lacks a lot of human touch. These generations don't seem to take into account many compositional techniques that are almost vital to make a comprehensive piece of music, such as motifs, dynamics, musical form, things like that. I found that there wasn't much for the ear to catch onto musically, no clear melodies,

rhythms, harmonic progressions etc. Because of this it can also be quite hard for a human to learn, adding on to the challenge of coordinating the strange rhythms between the hands. So it's cool, but very unhuman music and thus most likely difficult for humans to play.

17. I think if humans would take their time to learn this, the musical phrasing they would bring to the table could do a lot to make the pieces easier and more enjoyable to listen to. I think computer made music is very cool in that it really highlights the amount of complexity that goes into creating music as we would know it, namely through the human mind. So the kind of research you're conducting is very valuable indeed!

18. Wow this actually sounds very interesting! Sadly I'm not a very accomplished pianist either, but I'll leave this comment and upvote for visibility.

5 Discussion

~~The goal of this work was to determine whether it is possible produce musical pieces using Earth System model dataand to start to disseminate them, in a relatively passive manor.~~ The main goals of the work were to generate music using climate model data, to use music to illustrate some standard practices in Earth System modelling that might not be widely known outside our community, and to quantify the early dissemination of these pieces. Six pieces were generated, each piece used UKESM1 data, and the included a wide range of ocean model behaviour and methods. These pieces reached an audience of 251 people and were viewed 553 times in the first 90 days that they were published. Approximately half of views occurred in the first week that the videos were published. The views per day decreased after this initial two week period. Each new video received fewer total views than the previous videos during this initial period. ~~In effect, once the concept had been demonstrated to an audience, there was reduced enthusiasm from that audience to return to it. This suggests that to grow a YouTube channel, the content provider either needs to access new audiences or provide new and unique content.~~

The *Earth System Allegro* was the first video to be posted, and it received the most views, the largest number of total views, the highest opening day views, the most watch time and the most likes. The *Seven Levels of Climate Change* piece was the last video to be posted and received the least opening day views but also the least total views. In addition, each new video received fewer total views than the previous video over the entire 90 day time scale as well as during the initial period. This may be partially explained by each new video that was published typically resulted in the other videos being viewed as well, so new videos are unlikely to overtake older videos over their lifetime.

The piece that had the highest audience retention was the ~~Sea surface temperature aria~~*Sea Surface Temperature Aria*. This is not surprising either, as the end is arguably the most interesting part of this piece. This pieces ~~stats~~ starts slowly with a century of pre-industrial control by itself, then the historical dataset is added for another 165 years. In the final section of this video, the future scenarios diverge from the historical and pre-industrial control run. The global mean SST in scenarios rises rapidly in unison over the early part of the 21^{st} century, then diverge in the second half of the century. The *Sea Surface Temperature Aria* is also the most visually simple animation of the six pieces. Only one pane is visible in the video and much of the piece

only includes one or two voices at a time. It may be possible that this simplicity helps to hold the audience's attention. This piece is the work that is most similar to the other climate change music pieces like (**?**) and (**?**), described in sect. 1. In addition, this piece had the lowest opening day view count, but did not have the lowest total view count at the end of the 90 day time range.

The total number of views of the Earth System music playlist is very small when compared to the most popular YouTube channels, which may have millions of subscribers and views. However, when contrasted against other videos on Earth System modelling, the Earth System Music playlist has a comparable total view count. ~~This project was~~ As a comparison, the *UKESM short video introduction*, https://www.youtube.com/watch?v=hclsFbnmUdI, video was published in the CRESCENDO H2020 project YouTube channel on the 1^{st} of November 2017 and has received 183 views and zero likes or dislikes in the first two years since it was published. This is the only other video about UKESM1 on YouTube, and the Earth System Music playlist has received three times the total views in the first 90 days of the project. By itself, the Earth System Allegro video received more views in the first fortnight than the *UKESM short video introduction* received in two years. However, the YouTube video about Earth System Models with the largest viewership, *E3SM: DOE's New, State-of-the-Science Earth System Model*, https://www.youtube.com/watch?v=8Df96rx3i9g, has received 4479 views after 18 months online. Similarly, the NERC science YouTube channel has more than 700 subscribers at the time of submission, the most popular video *Anatomy of an earthquake - Professor Iain Stewart* has 82K views, (**?**). Both these videos have received significantly more views than the Earth System playlist.

The geographic distribution of the viewership based on the IP address was also included. This work originates in the United Kingdom and uses data from the United Kingdom Earth System Model, so it is not surprising that the United Kingdom is the largest source of viewers. It is likely that these works have been viewed outside those four countries, however no data is provided for 56.5% of the views, due to the restrictions imposed by YouTube.

Outside of the viewership statistics, a small number of people were sufficiently interested to subscribe to the channel or to like a video. Subscribing to a YouTube channel means that the future videos from that channel are more likely to appear on your main YouTube page.

This project was focused on demonstrating that we could use Earth System model data to generate music ~~, share it, and perhaps~~ and share it. While we hoped to improve the wider public's understanding of the methods used in climate change modelling, ~~rather than focusing on maximising viewer numbers.~~ the tools available to us within YouTube studio do not allow any way of assessing this.

The comments from social media were listed above in sect. 4 and were almost all positive and supportive. However, these comments are biased towards the author's friends, family and professional colleagues. These comments include several positive comments and praise, comments about the pieces themselves ("it gets dramatic at 1950-1960"), comparisons to other musicians or works of art (e.g. System of a Down, Herman Hess's book *The Glass Bead Game*, the Axis of Awesome medley). One person "didn't understand what the point is", and the final three comments contain some interesting insight into the musical side of the work.

6 Limitations and Future Work

As mentioned earlier, the main goals of this pilot study were to generate music using climate model data, to use music to illustrate some standard practices in Earth System modelling that might not be widely known outside our community, and to quantify the early dissemination of these pieces. We have successfully demonstrated that it is possible to generate music using our climate model's data. It is less conclusive whether we can teach the wider community about the methods of climate modelling. We have also found that the YouTube studio toolkit is not currently sufficiently capable to fully quantify the reach of these videos. We also make several suggestions for methods to reach a wider audience through improving the quality of the videos.

While we hoped to disseminate information about Earth System modelling to a wider audience, it ~~'s~~ is not possible to determine whether the audience learned anything about Earth System modelling using the metrics provided by YouTube studio or the comments posted on social media. Furthermore, it is not possible to determine whether the audience was composed of laymen or experts. As this was a pilot study, we did not go into greater detail to understand the audience reactions. Future extensions of this project should include a survey of the audience, investigating their backgrounds~~and~~ , 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 the current videos , the explanation~~

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 ~~is held in the~~ 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 YouTube studio, it is not currently possible to determine whether the viewers have ~~read or indeed understood the video explanation. To fully explain the methodology used by the modelling community, we could host live events explaining the science and then have live musicians perform the pieces.~~ expanded, read or understood the description section. When we have shown these videos to ~~scientific audiences~~ live audiences at scientific meetings and conferences, it has always been associated with a brief explanation of the methods. ~~This~~ In the future, this explanatory preface to the work could be ~~tailored for future pieces and~~ included in the video itself or as a separate video, as well as below the video in the description section.

If additional pieces were made, there are several potential ways that these could improve over the current set of videos. In future versions of this work, it should be possible to use ESMValTool (**?**) 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 ~~allow~~ make it easier for pieces to be composed ~~based on all the~~ using data available in CMIP5 and CMIP6 coupled model intercomparison projects. This broadens the scope of data by allowing other models, ~~but also~~ other model domains including the atmosphere and the land surface, and even observational datasets. For instance, we could make a multi-model 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 ~~include observational datasets in a piece~~distribute the source code that was used to make these pieces.

In their reflections on auditory graphics, **?** 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 **?**, but our focus was to produce and disseminate some relatively listenable pieces of music using UKESM1 data.

The two **?** 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 to the instruments used, and thus there was very little variability in terms of the timbres. ~~The~~ These pieces were all performed ~~as solo pianopieces~~by the same instrument, a solo piano, which limits the musical diversity ~~as well as~~ of the set of pieces. In addition, each dataset within 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 **?**, 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. ~~A human pianist~~ 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 ~~'s~~ 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 (**?**). Also, TiMidity++ uses the same ~~basic~~ 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. ~~In addition~~Finally, the published pieces had no mastering or ~~post production~~post-production. Even a basic mastering session by a professional sound engineer would likely improve the overall quality of the sound of these pieces. ~~Additionally,~~

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. ~~Furthermore~~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 every country in 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 ~~may be possible~~ 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.

We found that the bulk of the views originated from external links and direct links. This means that the sharing the videos over social media dominated over YouTube's in-built video suggestions. ~~It~~ While it was beyond the scope of this trial project, in future projects it might be possible to change the balance of external to internal traffic and 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.

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 (**???**). Future works should attempt to optimise the video thumbnail to attract a wider audience.

In terms of the reach, the authors expect there to be a modest increase in the view count upon the publication of this work. However, judging from the history of the video's audience size, and other videos in this field, we do not expect a significant change in the total number of views. If the goal of future projects were to increase the audience size, then it might be possible to reach a wider audience using a press release, a live performance, a public showing of the videos, 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 (**??**). However, view counts can rise exponentially when a single person or organisation with a large audience shares a video. Improvements to the music, the video, the description and the thumbnail make it more likely for an influencer to like, share, or re-tweet a piece, which could result in an ~~explosion~~ significant increase in the audience size and view count.

The videos in this work were posted to YouTube in an ad hoc fashion, as soon as they were finished. To maximise the number of views, online guides recommend consistent, scheduled in advance, weekly videos, and it's ~~best~~ been advised to publish them late in the week in the afternoons (**??**).

7 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 videos were posted on a YouTube channel and shared via the lead author's personal social media network. In the first 90 days of the videos being published, ~~the~~ they reached an audience of 251 unique viewers ~~, a total view count of 553.~~ and were viewed a total of 553 times. The viewers originated in at least four countries and largely got to the channel from a direct shared link of the video or the playlist. Approximately half of views occurred in the first week that the videos were published and the views per day decreased after this point. Each new video that was published typically resulted in the other videos being viewed as well.

Due to the way that these videos were disseminated through the lead authors personal and professional social networks, most of these 251 unique viewers will likely be familiar with the field of climate change research. However, it is less likely that the audience will be familiar with 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. These standard tools in the arsenal of climate modelling are not ~~widely known~~ yet widely appreciated outside our community. These six musical pieces open the door ~~to~~ on a new, exciting and fun ~~tool to add to our toolkit of how we interact~~ approach to how we engage with the wider public.

We have also discussed some ways to improve future iterations of this pilot study. To extend the reach, future works could be performed to a live audience, we could collaborate with musicians, and the ~~YouTube channel growth could be maximising through~~ viewership would likely be increased with improved video graphics, thumbnails~~performance and~~ , 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 ~~UKESM~~ 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 and the MIDI files 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, performed the analysis of the reach 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, L de Mora 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 number of unique viewers, total views, the average view duration and the time spent watching each video. This table also includes ~~youtube~~YouTube's unique video identifier for each video.

Video title	**~~Published~~ Publication date**	**Duration,** Minutes:seconds	**Experiments**	
~~Earth System Allegro~~ *Earth System Allegro* RxBhLNPH8ls	21-08-2019	1:02	Historical, SSP1 2.5	Drake ~~pas~~ Southern
~~Pre-industrial Vivace~~ *Pre-industrial Vivace* Hnkvkx4BMk4	21-08-2019	2:27	PI Control	Total Prin
~~Ocean Acidification in E minor~~ *Ocean Acidification in E minor* FPeSAA38MjI	22-08-2019	1:56	PI control, historical	
~~Sea Surface Temperature Aria~~ *Sea Surface Temperature Aria* SYEncjETkZA	02-09-2019	1:17	PI control, historical, SSP1 1.9, SSP5 3.4 OS, SSP5 8.5	
~~Giant Steps Spin Up~~ *Giant Steps Spin Up* fSK6ayp4i4w	13-09-2019	2:52	Spin up	Atlantic m Volume w Global surface
~~Seven Levels of Climate Change~~ *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 n

Table 2. Table showing the number of unique viewers, total views, the average view duration, the audience retention and the total time spent watching each video. The data in this table covers the 90 day range from the 21st of August to the 18th of November 2019

Video	Unique Viewers	Total Views	Average View Duration (minutes:seconds)	Retention %	Watch Time (hours)
Earth System Allegro	143	213	0:38	61	2.3
Pre-industrial Vivace	97	136	0:50	34	1.9
Ocean Acidification in E minor	68	89	0:59	51	1.5
Sea Surface Temperature Aria	37	59	0:52	68	0.9
Giant Steps Spin Up	21	31	1:39	58	0.9
Seven Levels of Climate Change	19	25	1:29	51	0.6
Total	251	553	0.51	53	8.0