The Impacts of Climate Change on Underwater Sound Propagation from Tidal Turbines

by

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The reality of climate change has led to an increased desire for renewable energy technologies. Recently, ocean energy has received increasing attention from the scientific community. Tidal energy specifically has immense potential, and as it is incredibly predictable there is the possibility of continuous energy generation from the ocean with the combined use of energy storage systems and tidal energy converters. However, before a mass implementation of tidal energy devices, their environmental impacts need to be better understood, and, in a warming climate it is critical to understand how the changing climate will influence these impacts. In this thesis, global climate models were combined with an Underwater Acoustic Simulator (UAS) to quantify the sound propagation from tidal turbines. This model was applied to 9 sample locations within Europe's marginal seas simulating sound propagation in modern day climatic conditions (seawater temperature and salinity) and in projected 2050 conditions. The turbine modelled was a 6-m OpenHydro open centre turbine due to its already environmentally conscious design. The locations were in the Baltic Sea, North Sea, and English Channel due to the propensity for tidal and wave energy in this region. The resulting sound propagation from the two simulations were subtracted from each other to calculate the change in Sound Exposure Level (SEL) at each location. The simulated changes at each location were averaged and fitted to a normally distributed probability density function (PDF) to predict how underwater sound propagation changes with the climate. In regards to spatial differences the results suggest minimal impacts from temperature and salinity differences between locations on underwater sound attenuation, but relatively large impacts from differences in bathymetry and topography. In regards to

changes over time the results showed that SEL tends to decrease with climate change, centering at around a -0.5 dB change. This is a very small change in comparison to the 185 dB of noise created by a tidal turbine. More to the point, six of the nine locations predicted an insignificant average absolute change (less than ± 0.3 dB). These results are helpful in understanding one of the many impacts of climate change on the planet's key environments, and expanding on how tidal turbines affect the ecosystem in which they are placed.

1. INTRODUCTION AND BACKGROUND

1.1 Purpose of the Study

For all of human history humans have been drawn to the ocean. This holds true today as about 40% of the population lives within 100 km of the coast [1]. And yet, marine renewable energy technologies have been looked past time and time again. A warming planet coupled with an increasing population and increased need for energy is driving a fast-moving desire for RE. This focus has been mostly on terrestrial energy options such as solar and wind, but the ocean, which makes up 71% of the planet's surface, has immense potential for energy generation [2]. The ocean has the potential to provide RE to surpass the world's energy demands, however it currently only accounts for 3% of energy produced globally [2]. In addition to energy potential, tidal energy has many advantages, such as geographic position and conservation of land resources [2].

While there are many advantages to tidal energy, research into its environmental impacts is widely lacking. Any time a new energy technology is introduced it is important to determine how said technology will interact with the ecosystem it is being placed in. Unlike wind and solar farms, which require a relatively small amount of development, tidal turbines must be fully submerged in the ocean, often being placed on the seafloor, leading to potentially large impacts on the surrounding environment [3]. There are many potential environmental impacts of tidal energy such as those studied by my former labmate Gabriella Pagliuca in her Masters Thesis on larval transport [4]. Her thesis was one of the main motivating factors for my research. In addition, there is a broad understanding of sound propagation from boats and underwater weapons testing using models similar to the one I used. However, the effects from tidal energy are widely lacking. Also, very little research has been done to explore how climate change might impact these effects. The preliminary goal of this study was to determine how sound from tidal turbines propagates through the surrounding ocean/water body. But equally important, this study was intended to determine the ways in which climate change impacts this sound. The motivation for renewable energy is our warming planet, so it is important to determine how this warming planet will affect the technologies being developed to combat it.

1.2 Hypothesis

One of the major impacts of climate change is a warming ocean, this contributes to a decrease in salinity as well as fresh water from ice caps melts into the ocean. Given this, how do we expect underwater sound to change? First, let's examine how the speed of sound might change. It is relatively easy to find the speed of sound in air (340 m/s) but underwater sound is a lot more complicated as it is greatly affected by temperature, salinity (and other dissolved impurities), mass density, and hydrostatic pressure [5]. There have been many equations derived to try and accurately determine the speed of sound with the currently most accurate equation holding 19 terms with coefficients of up to 12 significant figures [5]. A simplified equation for the speed of underwater sound as a function of Temperature (℃), Pressure (depth in m), and Salinity (ppt) is as follows:

$$C(T,P,S) = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.01T)(S - 35) + 0.16z$$

with T representing Temperature, S representing salinity, and z representing depth [5]. Even without examining the more complex equation it is clear that the speed of sound in water will increase with an increase in temperature and salinity. It is also clear that temperature has a larger impact on the sound speed than salinity does so it is fair to say that climate change will cause an increase in the speed of sound underwater.

Now, this study focuses on the Sound Exposure Level (SEL) in decibels so it's important to identify not only how fast the sound wave is moving, but also how it attenuates. Whenever any wave, not just sound, travels through a medium, the intensity, or amplitude, of that wave will decrease with distance [6]. In an idealized material the intensity of a wave will be reduced only by the actual spreading of the wave, however, seawater is not an idealized material [6]. In seawater, and other natural materials, there are further amplitudinal decreases by absorption (when the wave energy is converted to heat or other forms of energy) and scattering (the reflection of the wave), this combined effect is known as attenuation [6,7]. The amount of sound that is lost through this attenuation is part of the transmission loss (TL). The effects from scattering are minimal and entirely dependent on the location, so for the purpose of this hypothesis I will be focusing on the absorption effects. As a note, the impacts of absorption on the TL are small in comparison to the contributions from spreading [7]. The absorption effects are dependent on seawater properties (temperature, salinity, acidity, and frequency of the sound) [7]. At low frequencies (such as those created by tidal turbines as I will get into in section 1.3), the absorption in seawater is incredibly small, so its impacts are only measurable at large distances, and even then it is difficult to identity the portions of the TL that are from absorption [7]. Even so, since climate change will not impact loss due to spreading, let's examine the loss due to absorption. So, the general equation for the amplitude of an attenuating plane wave is as follows:

$$A = A_0 e^{-\alpha z}$$

where A_0 is the original amplitude, A is the new amplitude after the wave has traveled z meters, and alpha (α) is the attenuation coefficient [6]. Now, how can we determine alpha? When considering alpha from absorption losses, we must consider both viscous absorption from particle motion and the absorption by specific chemicals [7]. When discussing viscous absorption alpha is as follows:

$$0.00049fe^{-(T/27+D/17)}\ dB/km$$

With f as the frequency in kHz, T as temperature in ℃, and D as depth in km [7]. As I mentioned above, this is a very small effect for low frequency noise, but an increase in temperature decreases the absorption. Now, when discussing absorption from specific chemicals we are talking about boric acid and magnesium sulfate. These molecules have multiple stable states and thus can switch between these states based on pressure [7]. These state changes convert the energy from the acoustic pressure into heat, thus absorbing some of the sound waves energy, this is known as chemical relaxation [7]. Unlike viscous absorption, these absorption terms only affect lower frequencies, so they will have a larger impact on tidal turbine sound propagation [7]. I will not go into depth into the actual alpha equation as it is very complex, but for the purposes of this paper, please note that decreases in salinity increase low frequency absorption, and increases in temperature decrease absorption at frequencies <~780 Hz (for more information on underwater sound attenuation coefficients see [7]).

Given all of this information, how will climate change impact tidal turbine sound propagation? Firstly, I expect the speed of tidal turbine sound to increase. Secondly, I expect the changes in attenuation to be very small as the dominant factor (spreading) will not be impacted by climate change. However, I do expect these small changes to decrease the absorption, increasing the SEL, in places where temperature plays a dominant role, and increase the absorption, decreasing the SEL, in places where salinity plays a dominant role.

1.3 Background on Tidal Energy

There are many forms of ocean renewable energy, but the three main sources are waves, tidal currents, and thermal gradients. Wave energy converters generate power from waves on the ocean's surface, tidal energy converters generate power from the kinetic energy in tidal currents, and ocean thermal energy converters (OTECs) generate power from the thermal differences between cold deep water and warm surface water [8]. Ocean energies are gaining popularity and the US government predicts that ocean energy, including tidal energy, will be utilized initially to provide power to islands and coastal communities where it can be advanced and made more efficient/ cost-effective so it can break into broader markets [8]. While tidal energy itself is a subset of ocean energy, there are many additional subsets of tidal energy converters under the umbrella of tidal energy. In this section I will first explain tidal energy in general, then I will get into a few different varieties, and lastly I'll talk about tidal turbine noise.

Tidal energy is a form of renewable energy found in tidal streams in the ocean and some rivers. Tidal streams are currents of high velocity that are created through the periodic movement of the tides. These streams are magnified by inlets, lagoons, headlands, straits and other topographical features. Often, the shape of the seafloor pushes currents through tight channels or around headlands increasing the velocity of said currents. Tidal energy is a broad category that includes both tidal range energy - energy generated from vertical tidal motion due to gravity - and tidal stream energy - kinetic energy generated from tidal current velocities [2]. Currently, tidal range energy is much more developed than tidal stream energy, and many tidal range power stations have already been developed. While tidal stream energy is not very developed, it has huge potential. For this project I am focusing on tidal stream energy. Tidal stream energy converters are turbines that extract the kinetic energy from currents converting their mechanical energy into electrical energy [9]. When these turbines are set in rivers, oceans, or tidal currents, they generate hydrokinetic power due to the kinetic energy from the water. This power can be represented by the following equation:

$$P = \frac{1}{2} A v^3 \rho$$

with P representing power in Watts, v representing the current velocity in m/s, A representing the area covered by the turbine blades in m^2 and rho(ρ) representing the density in kg/m^3 [10]. The minimum current required to operate a hydrokinetic device is typically 2–4 knots (1–2 m/s), but optimal currents are in the 5–7 knot (2.5–3.5 m/s) range [11]. There are many types of turbines including vertical or horizontal axis turbines, open centre turbines, and tidal kites. Tidal kites are advantageous because they can harness low velocity offshore currents *as well as* high velocity tidal currents [8]. These are in the form of a "kite" secured underwater which uses flaps to move across a particular tidal stream in a fixed pattern shown in Figure 1.1 [8].

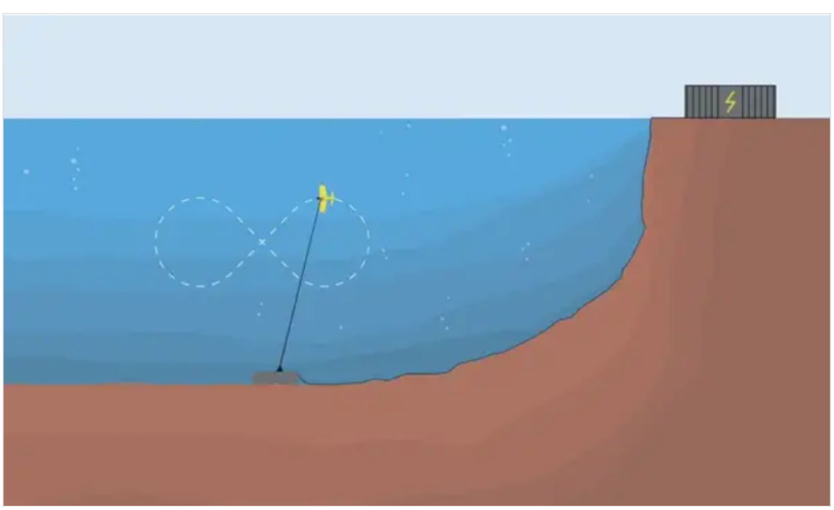


Figure 1.1 Illustration of the movement of a tidal kite [figure from 12]

This movement increases the speed of the water that flows across its turbine blades allowing more energy to be extracted [8]. Horizontal axis turbines are very similar to those used in wind generation as you can see in Figure 1.2. However, they are much smaller as the density of water is 800 times greater than air so even with less area covered by the blades more energy can be generated [2].

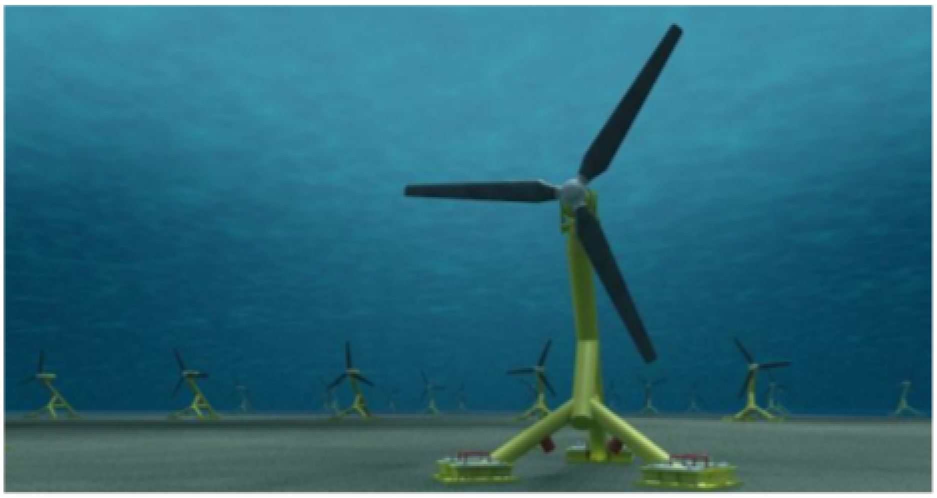


Figure 1.2 Artist's impression of horizontal axis tidal turbine array [figure from 13]

As I mentioned earlier in this paper, the environmental impacts of tidal energy are not well researched, but the main environmental risks are known. These risks include underwater noise, habitat changes, and collision of marine life with the actual turbines [8]. The invention of the open centre turbine by OpenHydro aimed to solve that last problem. In order to assess the turbine with the least environmental impact my project focuses on a 6-m diameter OpenHydro open centre turbine. As you can see in Figure 1.3 the large open centre provides an escape route for marine life [14].

Figure 1.3 OpenHydro 6m Open Centre Turbine [figure from 15]

In 2006 OpenHydro was the first developer to have a tidal turbine device connected to the Scottish grid, and was thereafter the first to generate electricity for the UK as a part of the national grid [15]. They used the tidal test site off the coast of Eday named the Fall of Warness (this is one of the locations I tested, for more information see section 2.3) to install their first 250kW open centered turbine (this is the turbine pictured in Figure 1.3) which was designed to rest on the seabed [15]. Since the deployment of this first turbine, the technology has been heavily tested and developed to produce the lowest cost of energy and the highest outputs [14]. The design is incredibly simple, it contains only one moving part with no seals in order to reduce the amount of maintenance needed [14]. It also contains a permanent magnetic generator rather than a gear box [14]. The design itself is easily scalable and it requires no grease, oils, or other lubricating fluids that might pollute its marine environment [14].

In regards to the sound created by tidal turbines, there are two main sources; the mechanical noise from the turbine's generator and the sound produced by the blades pushing the water. The noise from the generator is usually around 20 000 Hz and at levels low enough it has little impact on the surroundings [16]. The noise from the blades on the other hand is concentrated in the lower frequencies, ranging from 50-3000 Hz but typically below 500 Hz [16, 17]. Risch et al. conducted an experiment using a 1.5 MW 3 bladed horizontal axis turbine to characterize its underwater noise [16]. They found that within 20m of the turbine the SEL was 40 dB above the ambient conditions at their location in Pentland Firth, this is 30-35 dB greater than the fluctuations in ambient noise seen between tidal states [16]. They also noted that at a distance of 2300 m from the turbine, the SEL was still 5dB above the ambient noise [16]. While this is not the turbine being studied in this paper, it gives a good idea as to what could be expected. The US DOE did a study on the impacts of tidal energy noise on fish in 2011 using the sound profile for a 6-m open centre turbine shown in Figure 1.4 [17].

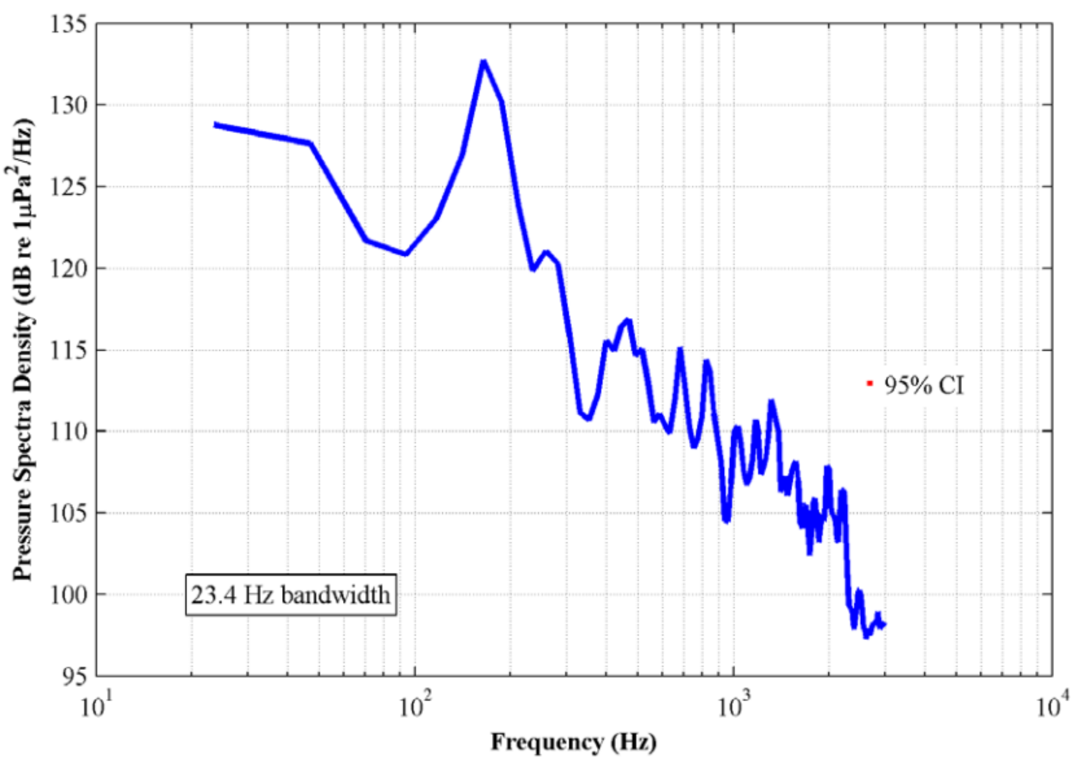


Figure 1.4 Recorded Spectra of Sound Generated by a 6-m-diameter OpenHydro Tidal Turbine [figure and caption from 17]

The above figure shows the relative SEL for each frequency associated with tidal turbine noise. As evidenced here, the 6-m open centre turbine follows the same frequency trends I described above, with the majority of the noise below the 500 Hz mark.

1.4 Environmental Impacts of Tidal Turbine Sound

As I mentioned briefly in the previous section there are three main impacts of tidal energy on the environment: physical collision of marine life, ecosystem disturbances, and noise. The open centre turbine design solves one of these problems, but still leaves the last two. To remain in the scope of this study I'll explore the third, noise. There is no way around it, hydrokinetic turbines will disturb their environment with noise during their installation/removal and while in operation. When discussing sound in water I am referring to the compression and rarefaction waves that propagate away from the source [17]. These waves can also propagate through the seafloor allowing them to travel very far from the turbine, very quickly [17]. It is also known that marine animals have used sound propagation throughout their history. For example, dolphins utilize noise to navigate, communicate, and hunt when they cannot rely on their sight [5]. It is also important to note that dolphins can produce noises with a wide array of frequencies and intensities implying a wide range of noises that could hinder some portion of their communication/ navigation [5]. Given this information, it is clear that tidal turbine sound could have major environmental impacts, but the extent to which is still unclear.

Sound with a large SEL (aka high intensity sound) can lead to behavioral changes and/or injury in marine mammals [18]. This sound could also potentially affect fish and invertebrates as I will discuss further below [17, 18, 19]. The effects from this noise is largely varied though, based upon the specific animals and on the specifications of the noise (intensity, frequency, and duration) [18]. Due to the varied nature of this impact experts have determined that the sound produced by tidal energy has the potential to have significant impacts, but that it contains large amounts of uncertainty as well [18]. So, what about the sound actually causes injury to marine animals? Essentially, the energy in the sound waves creates rapid pressure changes near aquatic animals which impacts their bodily gases leading to tissue damage [17]. There are two ways in which the state changes of bodily gases in fish can cause injury: (i) gases/natural bubbles in the swim bladder, blood, and tissues of the fish could expand and contract during these pressure changes potentially causing tissue damage if the change in volume of free gas is large enough or (ii) the solubility of these gases and other fluids could also change, causing the formation of additional free gas in arteries, veins, and organs of the fish [17]. In addition, fish hearing range contains the majority of tidal turbine noise, ranging from 15 Hz to 1 kHz [17]. They also utilize the complex acoustic environment that is the ocean in much the same way as marine mammals - to identify where predators, prey, and friends are located within their surroundings [17].

In a case study by Lossent et al [19] a turbine with an SEL at the source of 118 - 152 dB at frequencies form 40 - 8192 Hz was used to identify potential impacts on marine fauna. They found that the device created an acoustic “footprint” of a circle with a 3 km diameter, centered on the sound source [19]. Within this area of impact they found that the hearing apparatus of invertebrates, fishes, and marine mammals would very likely remain safe from physiological injury [19]. However, they did note behavioral disturbances to harbor porpoises within 1 km of the device, which is not a large concern for a singular turbine [19]. Although, given that most tidal farms will contain up to 100 turbines, the noise impacts, specifically the behavioral impacts, could be of greater concern for these farms [19].

2. METHODS

2.1 CMIP6 Climate Modeling

In order to assess the ways in which climate change might affect underwater sound propagation I needed to first determine how the ocean environment will change. The main factors that impact sound propagation as I mention above in section 1.2 are temperature and salinity. So, I utilized temperature and salinity data from a climate model for both my modern data and data for the year 2050. The climate model I used was created by my advisor, Professor Kristopher Karnauskas, and is a culmination of 43 different Coupled Model Intercomparison Project 6 (CMIP6) global climate models. The 43 models were re-gridded to a regular 3° grid using bilinear interpolation, and they were also linearly interpolated to a 1-m vertical grid. Of course, this model included a lot more data than just temperature and salinity, but the only data I used for this study was the potential temperature and salinity for the full depth of the global ocean. The model included the forced changes via monthly linear trend over 2015–2100 as well as the average over a base period 2015–2034. The linear trend in this model is based on the Shared Socioeconomic Pathways 5 (SSP5) scenario which focuses on fossil fuel development. This scenario predicts increasing development in all sectors, increasing use of fossil fuels, and technological advancements. In this scenario society would struggle with mitigation, but would have no struggles with adaptation.

In this study I used the averaged base period for the modern temperature and salinity data that I inputted into the sound propagation simulation I describe below in section 2.2. For the 2050 data I took the average over the base period and added 420 (35 years in months) times the monthly linear trend for each variable. From this temperature and salinity data I used Matlab to solve for the density and soundspeed at each location. I also used Matlab to create depth profiles of the temperature, salinity, density, and soundspeed for each 3 degree zone that contained one of the locations I was testing. Figure 2.1 shows these depth profiles for the box associated with 57-60 degrees latitude and 19.5-22.5 degrees longitude, which is in the northern part of the Baltic Sea, and one of the locations I studied is in this box. Note that these profiles confirmed my hypothesis that the sound speed increases with time, at least minimally.

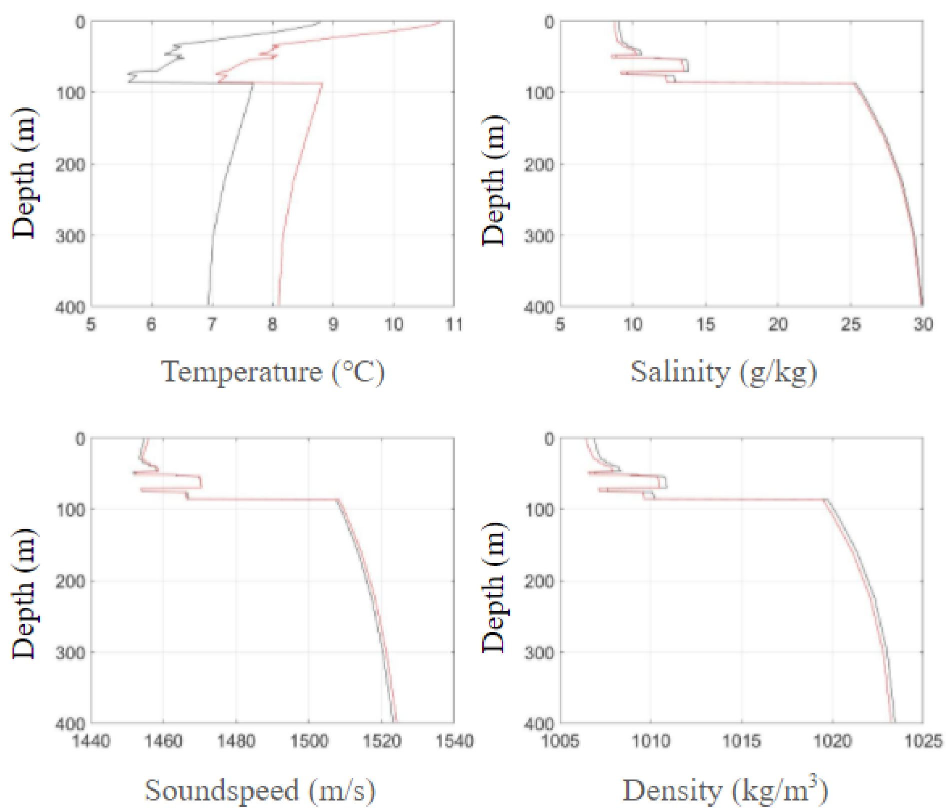


Figure 2.1 Depth Profiles of Temperature, Salinity, Soundspeed, and Density. With the black lines on each graph representing modern day and the red lines representing 2050

It is also important to note that at about 90 m there is a sharp change in temperature and salinity before they begin to fall/ rise respectively more steadily. These are known as the seasonal thermocline and the permanent halocline, however, since this location is in the Baltic Sea, which is a brackish body of water, the thermocline does not act the same as it does in the full salinity ocean. Here, temperature increases suddenly before beginning to drop, whereas in standard ocean water the thermocline marks a point of rapid decrease in temperature. This is due to the fact that the Baltic Sea is stratified into 3 distinct layers, the warm, well mixed upper layer, the cold intermediate layer, and the deep layer [21]. These differences between the locations in the Baltic Sea, and the North Sea and English Channel are important to keep in mind when reviewing the results of this study. It is also important to note that the density and sound speed profiles so heavily mimic the salinity profile because salinity is the major contributing factor to density and density is the major contributing factor to sound speed. On top of the depth profiles exemplified above, I used Matlab to create surface maps of the temperature, salinity, and change in each over the test period as shown in Figure 2.2.

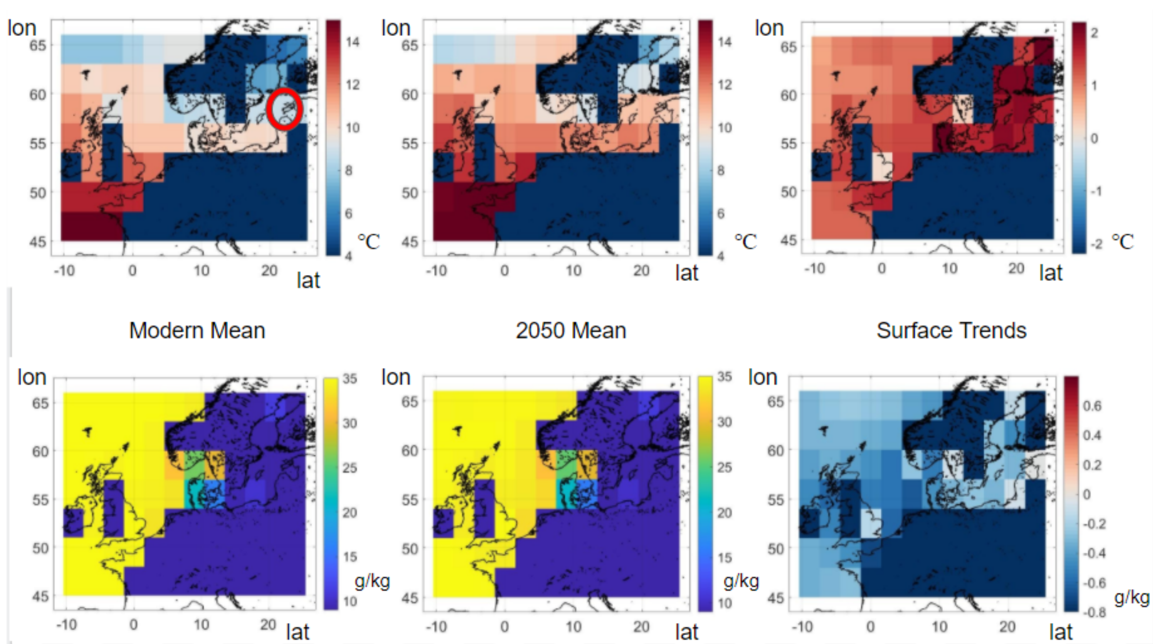


Figure 2.2 The three top graphs show Temperature in degrees Celsius and the three bottom graphs show Salinity in g/kg. From left to right these graphs show the modern mean surface temperature and salinity, 2050 mean surface temperature and salinity, then the surface trends for temperature and salinity between these two periods. The red circle on the top left map identifies the region (57-60 lat, 19.5-22.5 lon).

These maps show a grid of rectangles representing the 3 degree grid from the climate model. On the top left graph in Figure 2.2 the 3 degree box containing the depth profiles from Figure 2.1 is highlighted. While these maps were not used as inputs to the sound propagation model, unlike the depth profiles, they show very clearly the trends that could indicate differences in the sound propagation by location. The Baltic Sea shows a larger temperature increase than the North Sea or English Channel, and the south eastern portion of the North Sea shows the largest change in salinity, although this change is still quite small.

2.2 Underwater Acoustic Simulator

For the sound propagation simulation portion of this study I used the Underwater Acoustic Simulator (UAS) created by DHI. DHI is a Danish water software developer and engineering firm. In addition to the UAS, I used Matlab to run the pre and post processing scripts. I will explain the model in detail in this section, but as a brief overview for those who are not interested; this model utilizes temperature, salinity, soundspeed, pH, and bathymetry of the location, and frequency and SEL (sound exposure level) of the sound source as its inputs. The model takes all of the inputs and produces data on the SEL up to 15 km away radially from the sound source. I then took the SEL data and graphed it onto some maps shown in sections 3.1, 3.2, and 3.3. The reader who is primarily interested in model results may skip to section 3.

UAS is a Rage dependent Acoustic Model also known as RAM. It accounts for changes in the speed of sound, and volume attenuation in the water column [22]. The sound speed was described as a depth profile as found by me in Matlab from the CMIP6 data. As for the attenuation, UAS allows the user to input salinity, temperature, and pH depth profiles in order to determine this volume attenuation using the empirical model developed by Francois and

Garrison in 1982 [22]. This model (UAS) includes not only the sound which is propagated through the water, but also that which propagates through the seabed. It assumes that the waves are all compressional waves, so it models the seabed sediments as fluids [22]. I utilized a simplified seabed with 3 constant density, constant thickness layers with a lower boundary condition that terminated the physical solution domain in the form of an absorption layer several wavelengths thick to reduce the amount of energy reflected back from this lower boundary to close to zero [22]. In addition, the surface of the model is still water, which reflects back all sound [22]. As for the sound source, it is modelled as an omnidirectional point source (the sound propagates 360° around the source).

UAS is a 2D model which simulates the sound propagation in a vertical transect (r-z plane). I set the model to take a transect every 10 degrees resulting in 36 model runs for each point source. The sound source is automatically located at the start of the transect, in the leftmost boundary of the domain. I set the sound source to sit at 20 m below the still water surface so that I could have it at the same height in all of the locations, without worrying about it being below the seafloor in any. I also had the ability to set the sound level of the sound source (a tidal turbine in the case of this study) as a spectrum so the sound energy could vary per frequency band as shown in figure 2.3. This sound source input mimics that shown in figure 1.4. UAS is uniquely capable of solving the sound propagation for a sound source like this one (with multiple frequencies) in one run, and additionally it accounts for frequency sensitivity to environmental properties.

	Time	1:f [hertz]	2:SEL [dB re 1 mu-Pa^2*sec]
0	0	25	129
1	10	31.5	128
2	20	40	128
3	30	50	127
4	40	63	123
5	50	80	121
6	60	100	122
7	70	125	123
8	80	160	130
9	90	200	127
10	100	250	121
11	110	315	114
12	120	400	116
13	130	500	115
14	140	630	111
15	150	800	113
16	160	1000	109
17	170	1250	108
18	180	1600	105
19	190	2000	108
20	200	2500	99

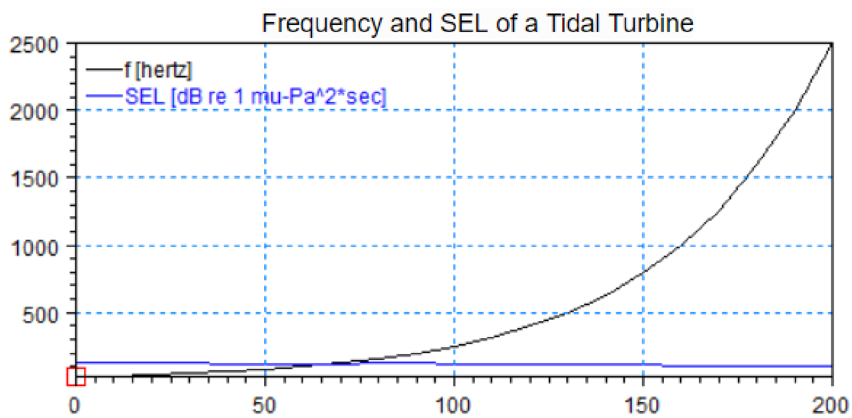


Figure 2.3 Input for the soundsource of a OpenHydro 6-m tidal turbine with frequency in black and SEL in blue. The table shows the data in the graph.

This feature was very helpful as tidal turbines are broadband with differing SELs for each frequency band as I described in section 1.3 above. The spectral discretisation could also be specified in either octave bands, ⅓ octave bands, or 1/12 octave bands (⅓ octave bands for this study) with minimum and maximum centre frequencies specified as well (25 Hz to 2500 Hz). It is also important to note that this model does not include a backscatter of energy (echo), so there is some uncertainty in the SEL at locations where the sound source is close to the coast.

2.3 Experimental Set-up

For this study, I looked at turbines in a variety of locations (10 total, although there are only results from 9 which I will explain more in section 3.6) throughout the Baltic Sea, North Sea, and English Channel as shown in figure 2.4.

Figure 2.4 Map of the Baltic Sea, North Sea, and English Channel with simulation locations noted. Pink bubbles represent existing tidal or wave energy locations and yellow bubbles represent areas of high potential energy generation.

Ideally, hydrokinetic turbines are placed in locations that have a stable current throughout the year. It is also important that the locations not be prone to serious floods, turbulence, and/or large periods of low water. For these locations, I have a mixture of locations where tidal energy is currently being produced and ones I have identified as having high potential energy generation. When looking for theoretical locations I focused mostly on topography but also on infrastructure. When choosing existing locations I looked for current tidal or wave energy farm locations [23, 24, 25].

Once I identified all the locations I wanted to study I found the temperature and salinity data for the appropriate 3 degree grids, solved for density and soundspeed, inputted this information into UAS and began running the simulations. I first tested each location with the modern climate data, then I tested them all again with the 2050 data. Once I had the simulation results, I formatted them into graphs of propagating SEL. I then subtracted the SEL data for the modern day simulations from the 2050 simulations to find the change in SEL at each location. Once I had this change in SEL as a function of theta and R, I used Matlab to average all of the values for each location to determine the total average change in SEL at each location. Once I had these values, I used Matlab again to find a normal probability density function (PDF) that could represent this data. This allowed me to assess both how sound propagation is impacted by the location of the turbines as well as how climate change impacts this sound propagation.

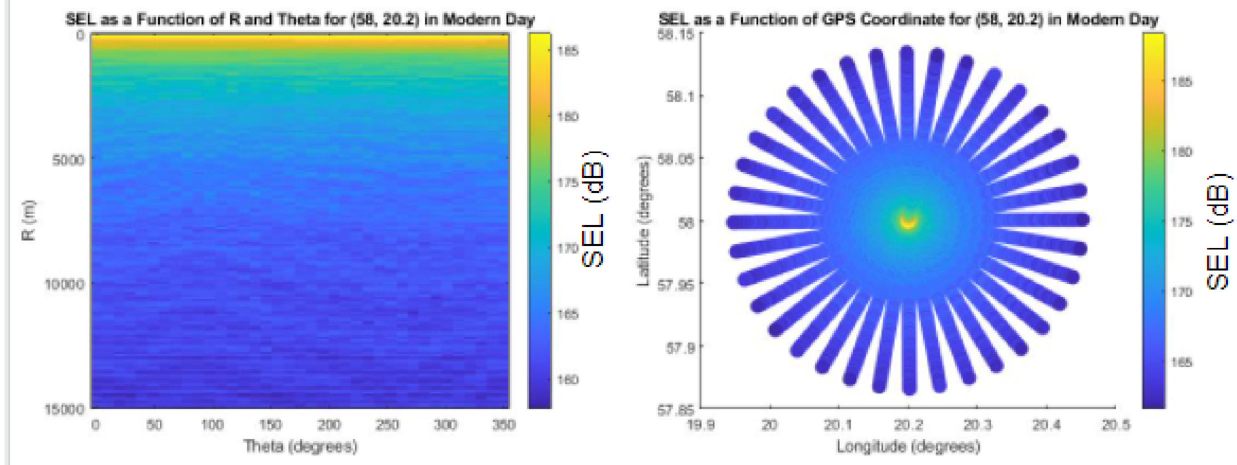
3. RESULTS AND DISCUSSION

3.1 Simulation Results For Modern Day and 2050

In this section I have the results for 9 simulation runs using data from the base period in the climate model, as well as results for 9 simulation runs at the same 9 locations but using the 2050 data. As a reminder, this data is the data from the base period plus 420 times the monthly linear trend from the CMIP6 climate models described in section 2.1 above. Due to the proximity to land of location 7, those results could not be included in this paper. The results shown in figures 3.1 - 3.9 in this section represent the SEL at each of the remaining locations. The graphs have the SEL in dB represented by the colours seen in the colorbar to the right of each graph. For the graphs on the left, the y-axis is the radius from the sound source in meters with the top being closest to the sound source and getting further away as it goes down, evidenced by the colours getting darker (sound is decreasing in intensity as it gets further away from the source). The x axis is the radial direction theta in degrees, so 0 and 360 point directly north, 90 points east, 180 points south, and 270 points west. The graphs on the right are scatter plots of the values in the graphs on the left, but in a circular array, with the x axis being longitude and the y axis being latitude. Note that the right hand plots look slightly odd, this is because the data points overlap with each other slightly, but I included these plots to give an idea visually of what is actually happening to the sound. In each figure, the modern day results are on the top, and the 2050 results are below. Notice that the 2050 and modern day simulation results look very similar. This is because the shape of the sound propagation is caused by the bathymetry of the ocean floor, which remains unchanged.

The first location, pictured in Figure 3.1, is representative of a location at (58, 20.2) which is in the north-eastern portion of the Baltic Sea. Refer back to figure 2.4 to see this location and the following ones on a map.

(a)



(b)

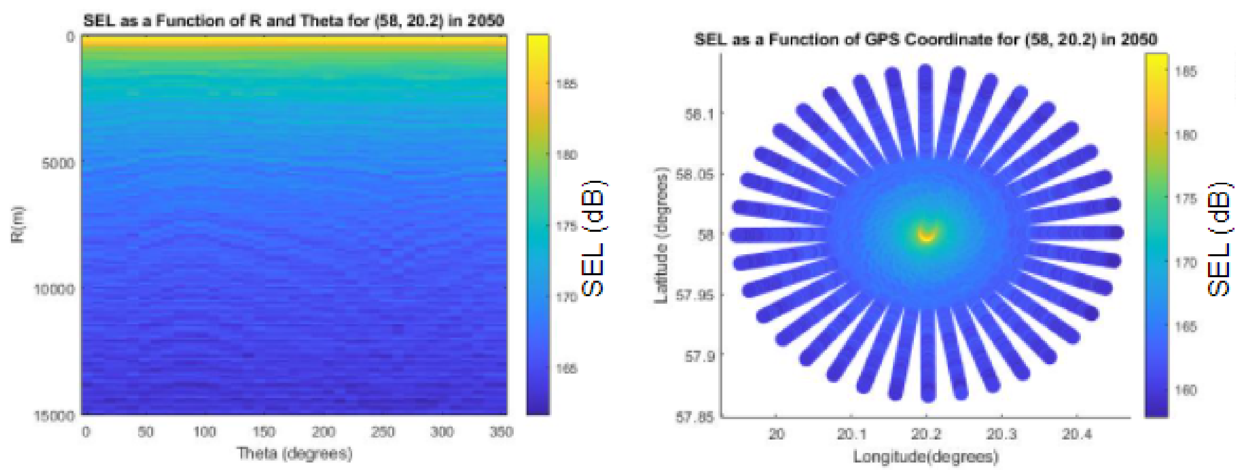
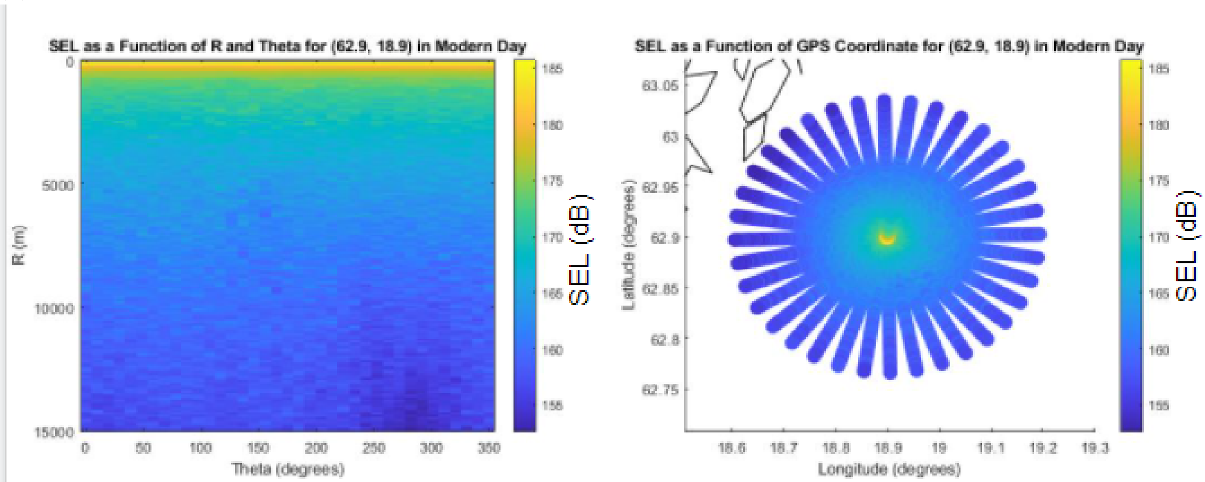


Figure 3.1 (a) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (58, 20.2) using modern climate conditions. (b) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (58, 20.2) using 2050 climate conditions

Interestingly, while the sound is on average decreasing as it propagates out from the source, there are portions where it increases slightly, showing places where the bathymetry of this location pulses the sound waves creating time independent waves. These permanent highs and lows of the sound waves are visible in both the 2050 and modern day maps. These “waves” are in the exact same locations in modern day as 2050 because this model does not account for changes to the seafloor over this period. In agreement with most of the other locations, location 1 has an SEL at the source of around 185 dB which reduces to a bit under 160 dB 15 km away from the source. This represents a Transmission Loss (TL) of around 25 dB. The second location, pictured in Figure 3.2, is representative of a location at (62.9, 18.9) in the northernmost portion of the Baltic Sea at the edge of the Gulf of Bothnia.

(a)



(b)

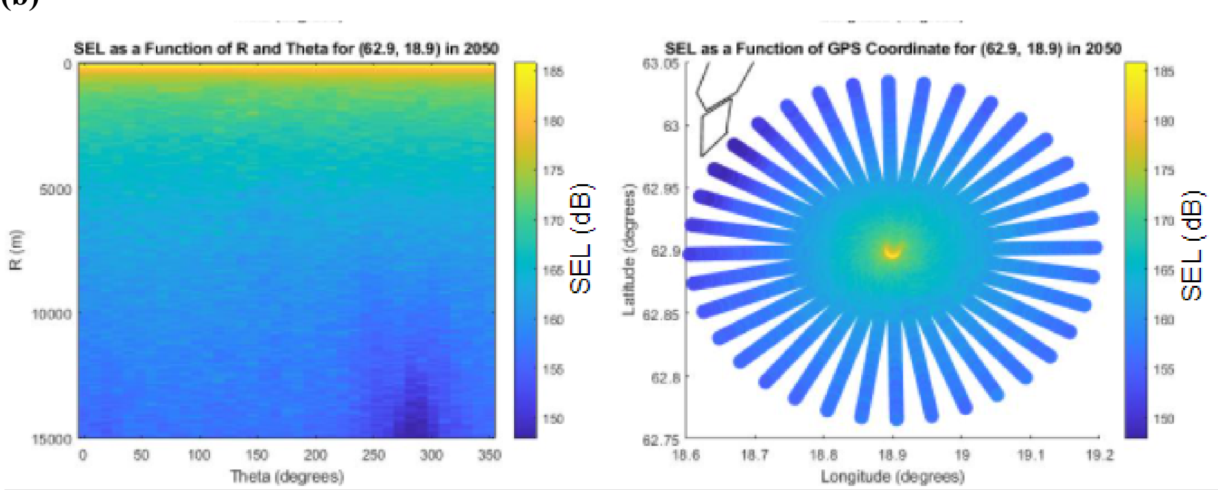
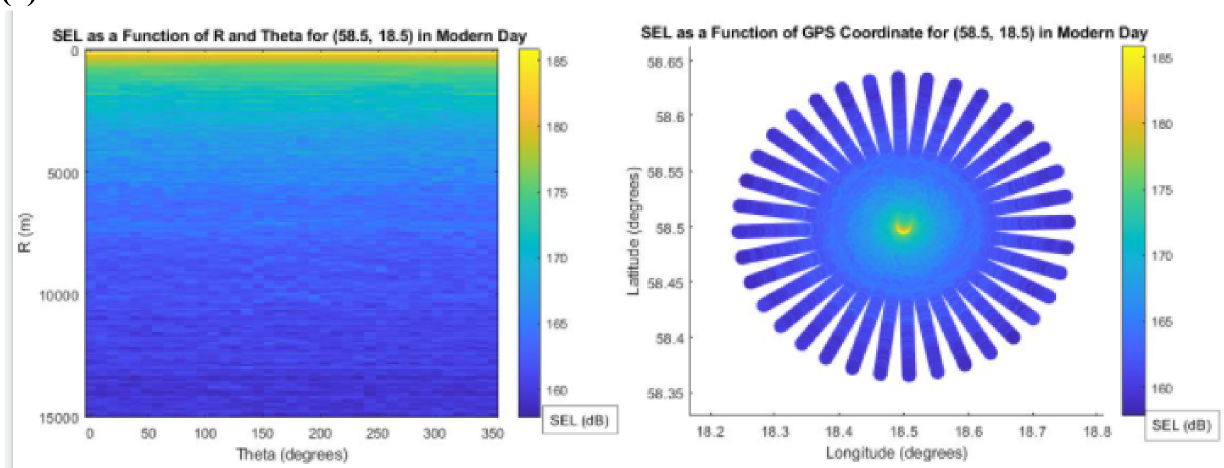


Figure 3.2 (a) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (62.9, 18.9) using modern climate conditions (b) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (62.9, 18.9) using 2050 climate conditions

On the map on the right in Figure 3.2, the coastline is visible in the top left corner, this is Sweden. Here, the SEL drops from about 185 dB again to around 155 dB, 5 dB lower than location 1. This increase in the TL at this location makes sense as it is North of location 1, so the cold water leads to an increase in the TL. The tidal turbine here is 15 km away from the coast, so the coast is visible, but does not directly interfere with the sound propagation mapping. However, it does interfere with the SEL calculations. Evidently, the SEL decreases more rapidly as the sound nears the coast than it does in open water. This is not what we would expect, but since the sound model does not include echo, this makes sense. In reality, while yes, some of the sound would be absorbed by the coast, some of it would be reflected (or echoed) back towards the sound source, increasing the SEL on that side of the source. The third location, pictured in Figure 3.3, is representative of a location at (58.5, 18.5) in the central portion of the Baltic Sea near location 1.

(a)



(b)

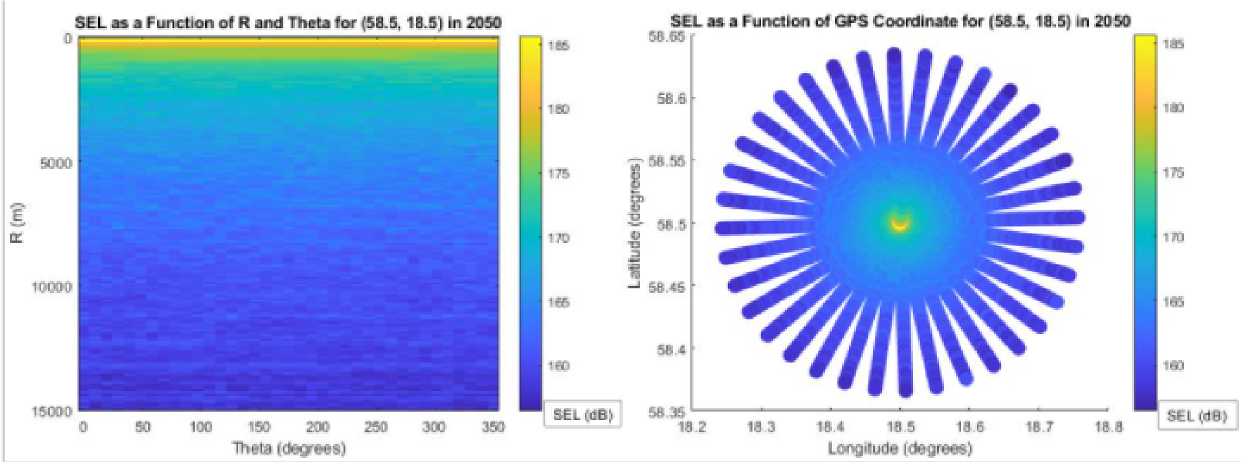
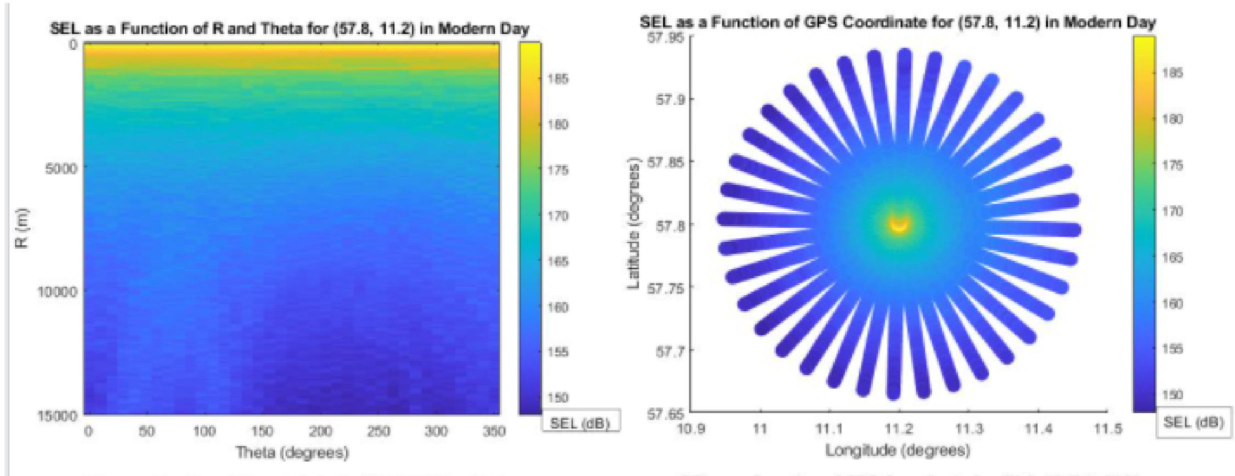


Figure 3.3 (a) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (58.5, 18.5) using modern climate conditions (b) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (58.5, 18.5) using 2050 climate conditions

The sound propagation at this location very closely mimics that at location 1 with a TL of about 25 dB. This makes sense as both of these locations are near each other in the Baltic Sea so their ambient conditions are very similar. However, I would expect these locations, along with locations 2 and 5 to have the highest TL due to the lack of salinity in this area, however, when hypothesizing the attenuation I was using equations for sea water, not brackish water, so my predicted ideas do have some uncertainty. The fourth location, pictured in Figure 3.4, is representative of a location at (57.8, 11.2) in Skagerak, between the North Sea and the Baltic Sea.

(a)



(b)

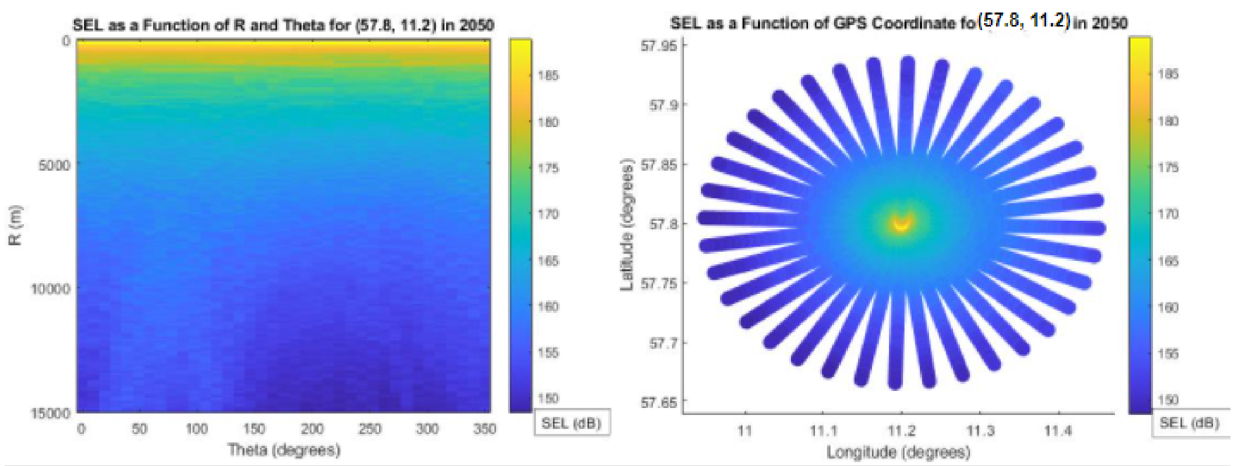


Figure 3.4 (a) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (57.8, 11.2) using modern climate conditions (b) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (57.8, 11.2) using 2050 climate conditions

The TL here is around 30 dB, going from 185 dB at the source to around 155 dB 15 km out. This closely mimics the TL at location 2. This might seem odd at first, given that location 2 is much further north than this location, but the bathymetry at each location is quite similar, and this location does have a relatively low temperature. They are both in narrow straits, which is why they are both being used for tidal energy generation, but could also explain why their sound propagation is similar. The fifth location, pictured in Figure 3.5, is representative of a location at (55.2, 12.5) in the south-westernmost portion of the Baltic Sea at the edge of Kattegat.

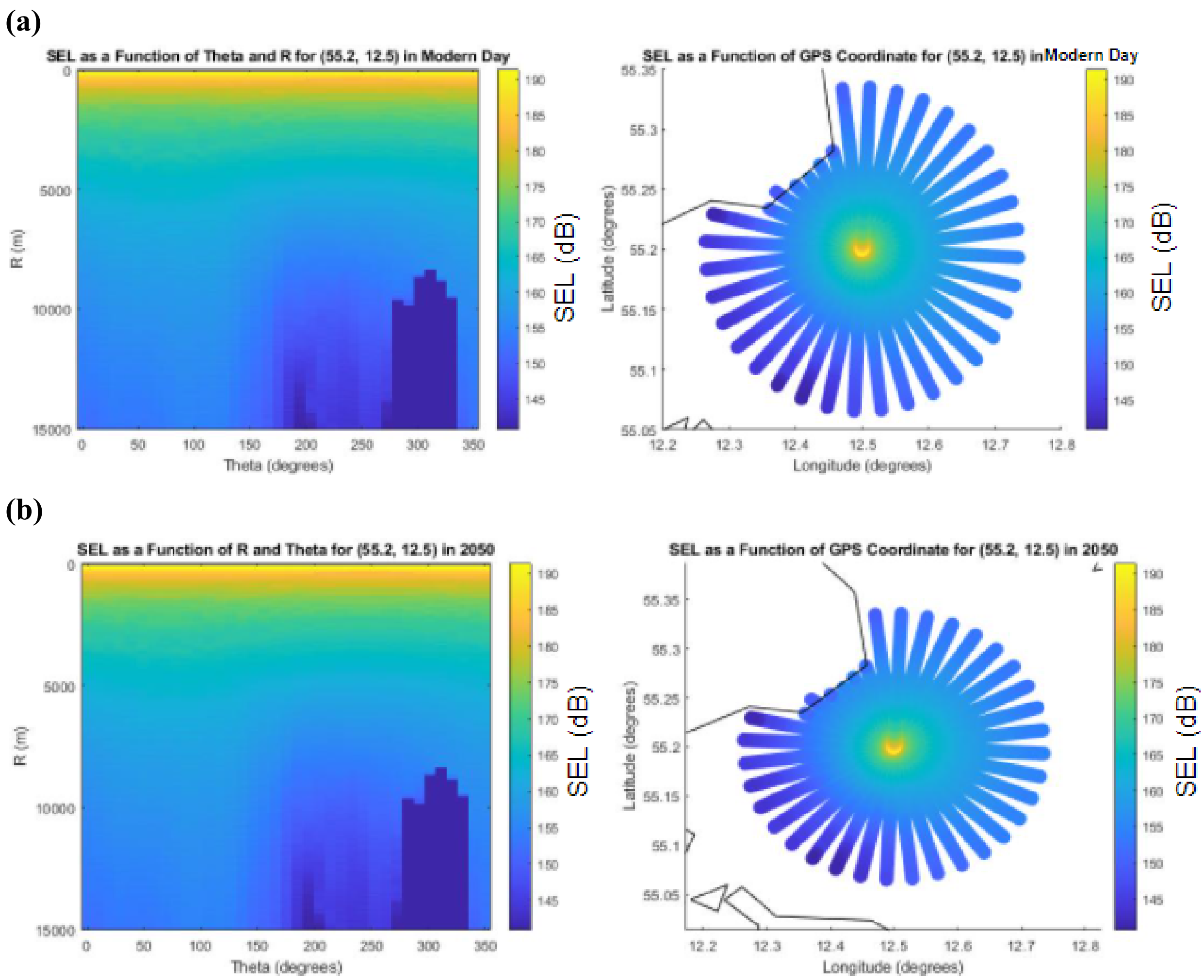
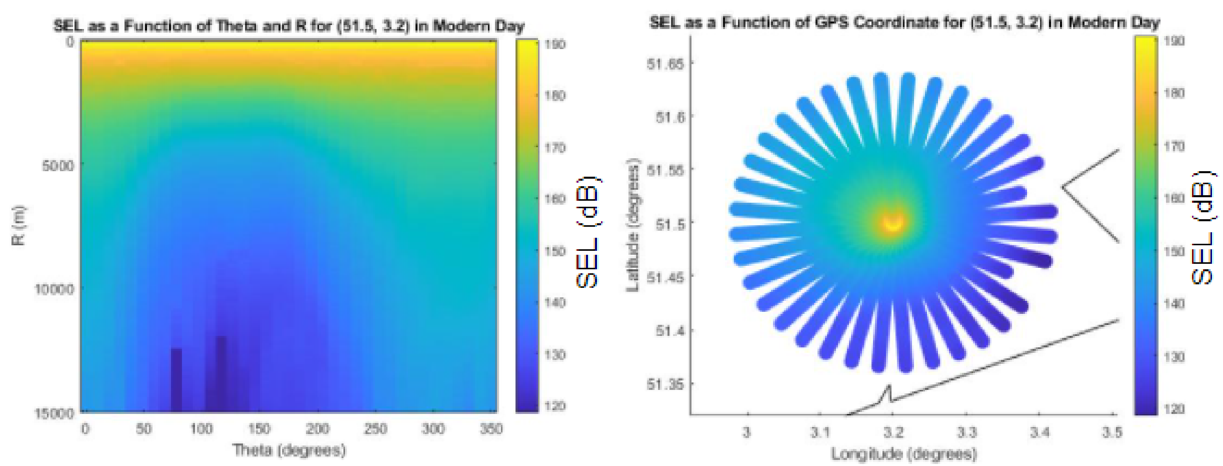


Figure 3.5 (a) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (55.2, 12.5) using modern climate conditions (b) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (55.2, 12.5) using 2050 climate conditions

Again, this location is up close to the coast, this coastline is representative of Denmark. This time, however, the coastline keeps the model from calculating the SEL for the full 15 km radius. This is clear in the right hand graph in Figure 3.5 but on the graph on the left this lack of data is represented by the dark blue colour seen in the bottom right from 270 -330 degrees. Again, the very dark portion around 200 degrees is due to the land mass near there not echoing any sound back. For the “normal” portion of the propagation the SEL goes from around 185 dB to around 155 dB giving a Transmission Loss of around 30 dB, the same as location 2 and 4. This is not quite what I would expect as this location is warmer than location 2, but it is only slightly warmer, and the lack of echo could be having an impact on the TL throughout the entire propagation area. In addition, this location is also in a narrow strait, like locations 2 and 4. The sixth location, pictured in Figure 3.6, is representative of a location at (51.5, 3.2) in the English Channel off the coast of Belgium.

(a)



(b)

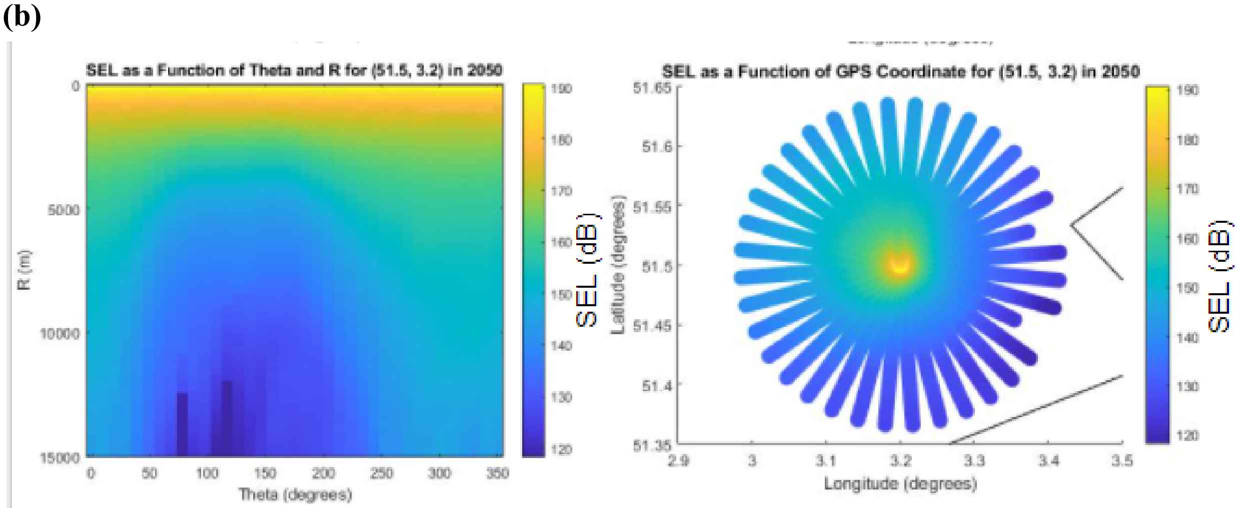
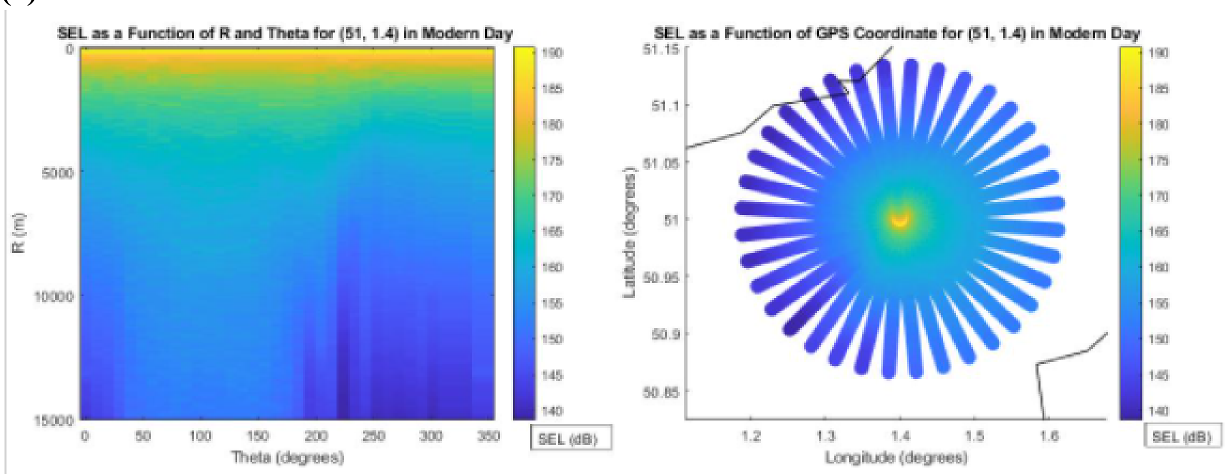


Figure 3.6 (a) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (51.5, 3.2) using modern climate conditions (b) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (51.5, 3.2) using 2050 climate conditions

Again, there are 2 angles in which the model could not simulate the sound due to a close proximity to land, and the region between 50 and 200 degrees is likely underestimated. Even given this, the rest of the area of propagation reduces from around 185 dB to around 150 or 145 dB giving a TL of almost 40 dB. This is a very large TL given how much saltier and warmer the water is here than the previous 5 locations, but again, its proximity to the coast likely impacted this TL value. Again, the seventh location had some issues with the post processing script so I will skip ahead to the eight location. The eight location, pictured in Figure 3.7, is representative of a location at (51, 1.4) in the English Channel slightly south-west of location 6.

(a)



(b)

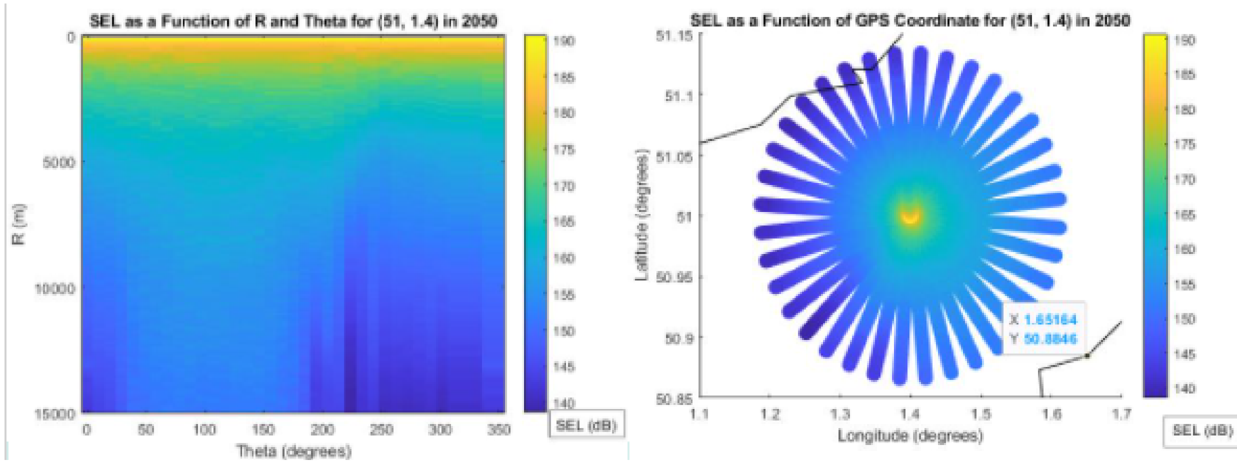
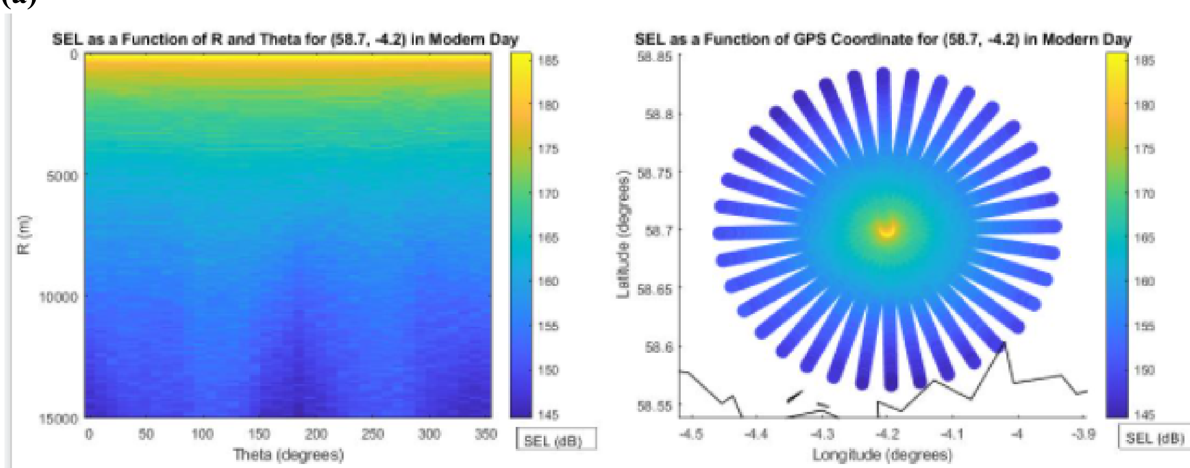


Figure 3.7 (a) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (51, 1.4) using modern climate conditions (b) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (51, 1.4) using 2050 climate conditions

At this location the SEL reduces from 185 at the sound source to around 155 (ignoring the heavily reduced section by the coastline) giving a TL of 30 dB, consistent with locations 2, 4, and 5. All four of these locations are in straits, but don't have much else in common, showing that the bathymetry and topography of the location has a larger impact on the sound propagation than I had initially thought. The ninth location, pictured in Figure 3.8, is representative of a location at (58.7, -4.2) in the western portion of the North Sea off the coast of Scotland.

(a)



(b)

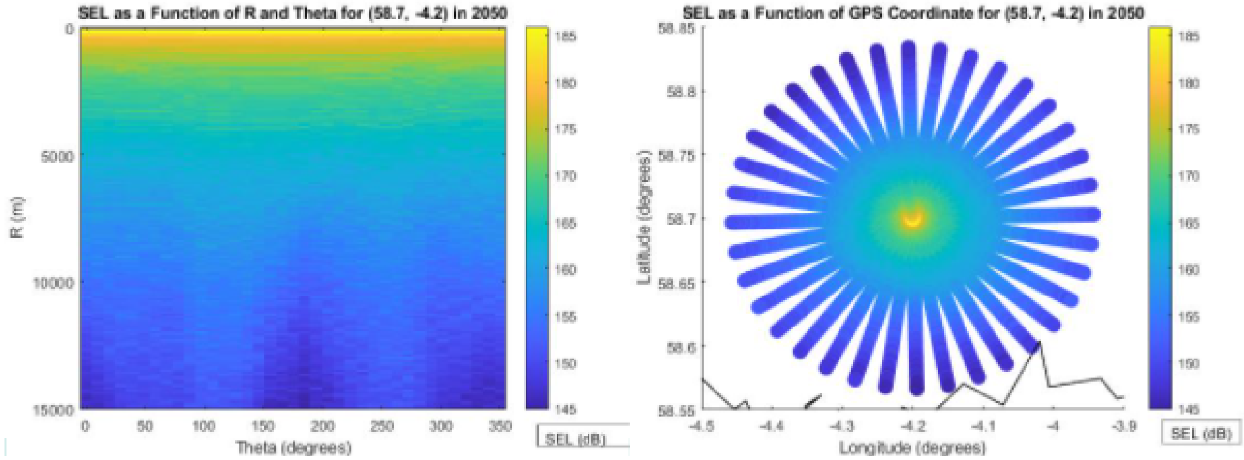
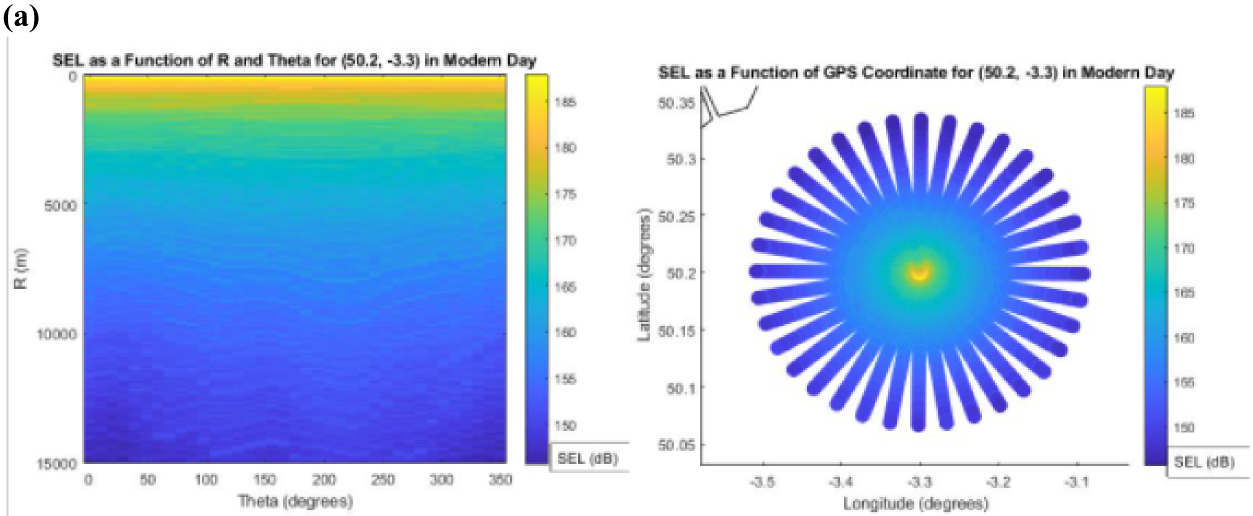


Figure 3.8 (a) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (58.7, -4.2) using modern climate conditions (b) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (58.7, -4.2) using 2050 climate conditions

This location might appear to be close to the coast on all sides based on the large TL on all sides, but there is open ocean from ~270 degrees to about 30 degrees. Given this, the average TL for this location, ignoring the coastal section, is ~35 dB going from 185 dB at the source to ~150 dB at 15 km. The tenth and final location, pictured in Figure 3.9, is representative of a location at (50.2, -3.3) in the western portion of the English Channel.

(a)



(b)

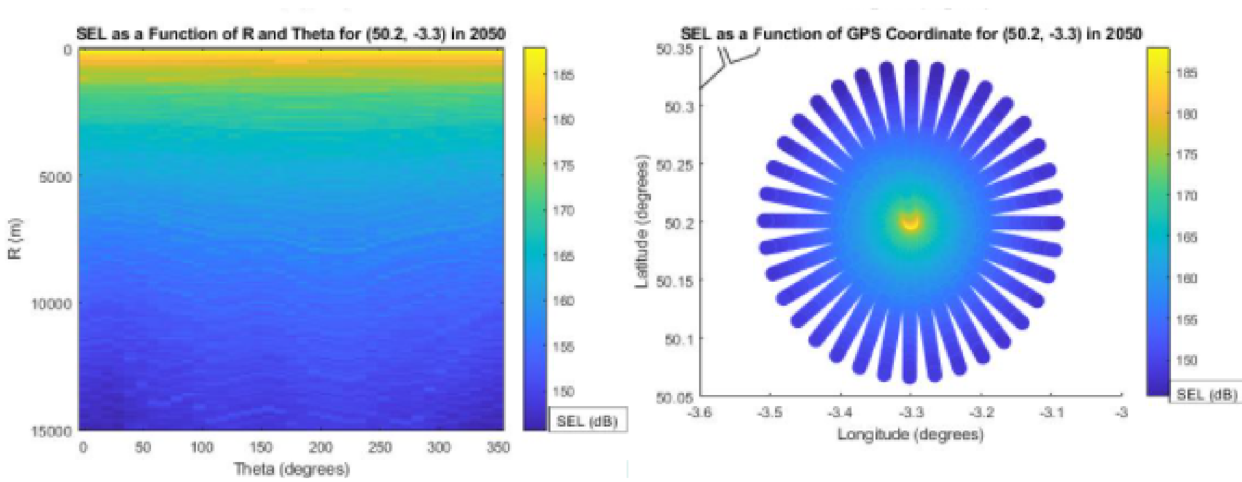


Figure 3.9 (a) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (50.2, -3.3) using modern climate conditions (b) Two graphical representations of the Sound Exposure Level (SEL) of a tidal turbine propagating away from a point source at (50.2, -3.3) using 2050 climate conditions

This location has coastlines from about 300 degrees until around 50 degrees, as evidenced by the darker colours in that region. In the remaining region the SEL decreases from 185 dB at the sound source to a little over 150 dB at 15km, equivalent to a TL of about 35 dB. It is interesting to note that locations 6, 8, 9, 10, which are in the true ocean, have TL's that are on average almost 10 dB higher than locations 1,2,3,4, and 5, which are in brackish water. Based on my predictions I would expect an increase in salinity to decrease the overall TL as it increases the soundspeed and decreases the attenuation, however these results show the exact opposite. While this was not what I had predicted, I am not that surprised, as I noted in section 1.2 low frequency sounds do not experience much attenuation outside of spreading losses. So, the differences I see here are more than likely mostly due to differences in bathymetry/ topography of the locations.

3.2 Impacts of Climate Change

Now, it is clear that the changes in SEL between modern day and 2050 are not significant enough to be able to tell by eye. So, I used the data from the 2050 simulation runs and subtracted the data from the modern day simulation runs in order to find the change in SEL at each location. The following graphs (Figures 3.19 - 3.27) use a color bar, similar to those used above, however the colors represent the change in SEL, with reds representing positive change, blues representing negative change, and white representing no change. These graphs also mimic the left hand graphs from the above figures, with the SEL as a function of R and Theta. The first location, shown in Figure 3.10, is very interesting as it shows a relatively significant negative change in SEL.

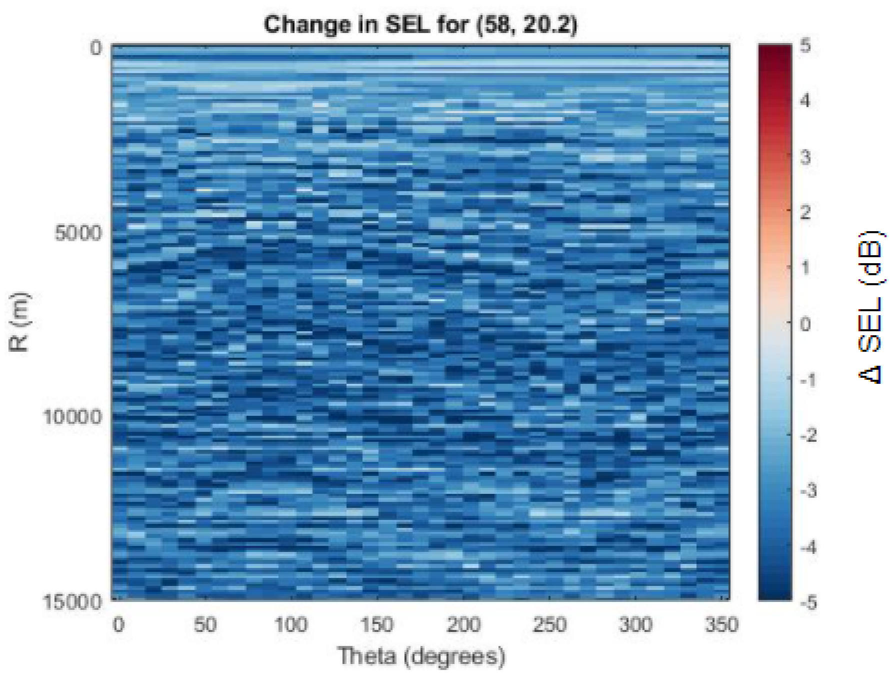


Figure 3.10 Graphical Representation of the Change in Sound Exposure Level (SEL) at (58, 20.2)

This location showed the most change in comparison with the other locations with an average decrease of 3.51 dB. The reason this result is so interesting is that this location shows the most temperature increase of any other location simulated in this study. While it showed minimal change in salinity, the temperature increase should have theoretically indicated a decrease in the attenuation at this site. Again, this is a site in brackish water, so that might account for this discrepancy. Also, interestingly, the change in SEL follows the "waves" I noted in sections 3.1 and 3.2 above. The second location, shown in Figure 3.11, is also quite interesting in regards to how the change in SEL reacts to the presence of a coastline.

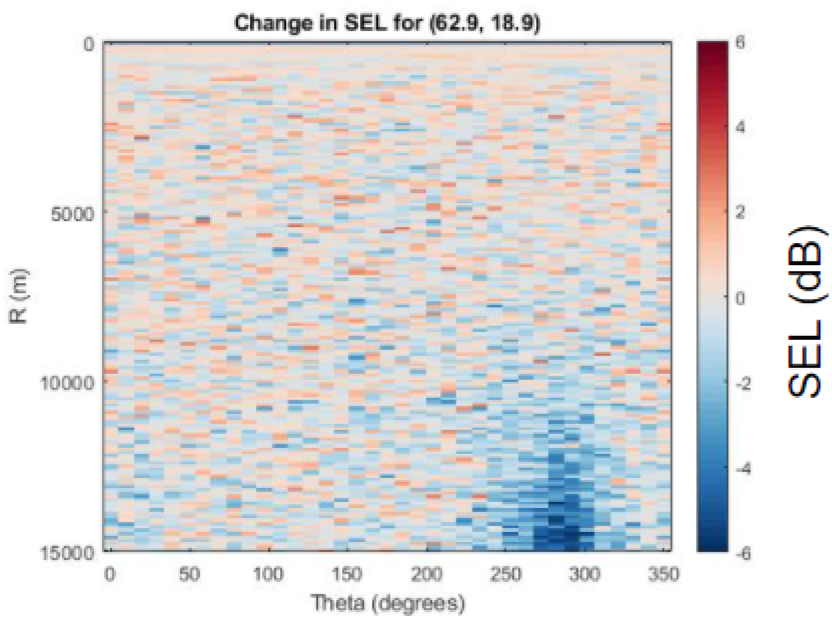


Figure 3.11 Graphical Representation of the Change in Sound Exposure Level (SEL) at (62.9, 18.9)

Evidently, as the sound waves get closer to the coast the amount of change in SEL increases. In the majority of the area of propagation for this soundsource the change in SEL is sporadic, but mostly positive. In fact, if the coastal section is removed the average change in SEL would be only slightly below 2 dB, but the actual average change is -0.756 dB. The third location, shown in Figure 3.12, is also quite sporadic, like location 2.

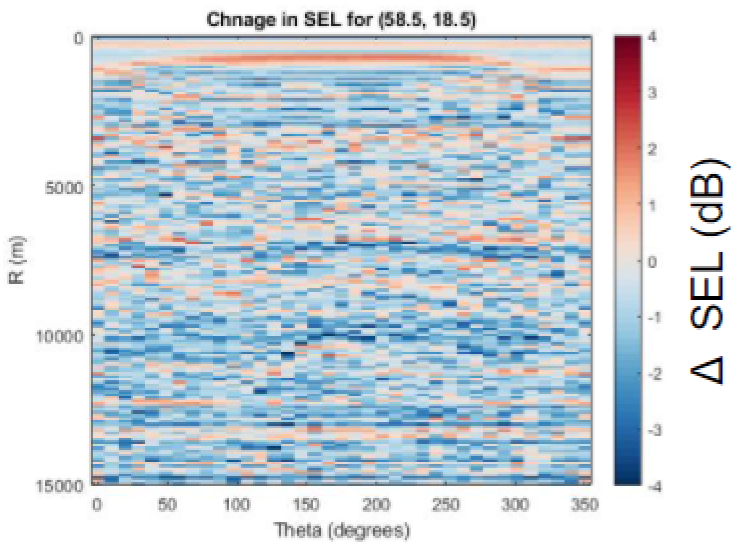


Figure 3.12 Graphical Representation of the Change in Sound Exposure Level (SEL) at (58.5, 18.5)

Here, along the “waves” the change in SEL switches between being positive and negative while maintaining the same shape as the modern day and 2050 graphs. It's interesting that while the changes seem quite random, they are a bit larger than many of the other locations. And, even with the sporadic nature of the changes the average change in SEL is -0.992 dB, which is the second largest change, behind location 1. The fourth location, shown in Figure 3.13, is one of the few that has a positive average change in SEL.

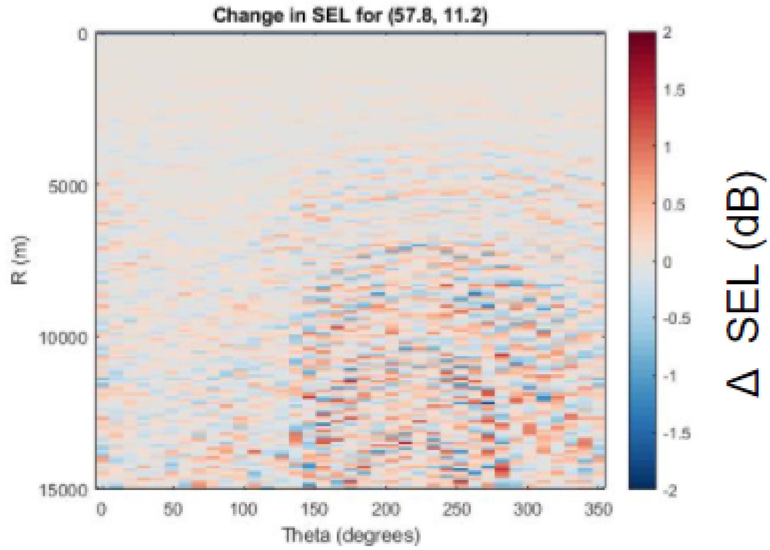


Figure 3.13 Graphical Representation of the Change in Sound Exposure Level (SEL) at (57.8, 11.2)

Even though the average is positive, it is quite close to 0 (0.0493 dB) as the changes are quite sporadic again. Even given this randomness though, the area where the sound is reacting to the coastline is very clear, having the most change in SEL. The fifth location, shown in Figure 3.14, has the second smallest change of all the locations.

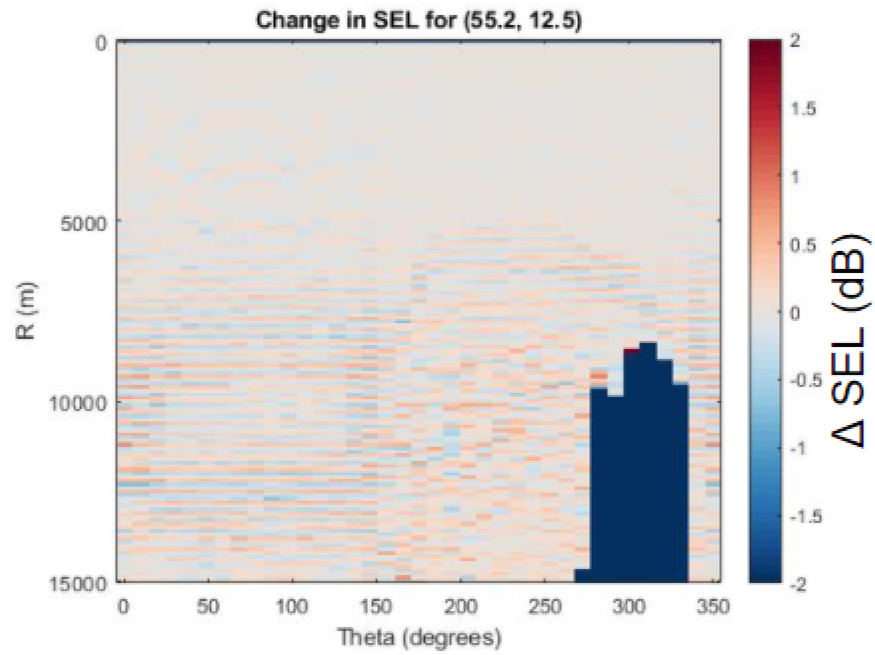


Figure 3.14 Graphical Representation of the Change in Sound Exposure Level (SEL) at (55.2, 12.5)

Even so, the area impacted by the coastline is again clear. Interestingly this location is also one of the few that has a positive average change in SEL (0.0367 dB), showing the least amount of positive change. This makes sense, as it is very close to location 4, and it also has very similar topography, so the fact that the changes are quite similar is unsurprising. The sixth location, shown in Figure 3.15, is unique in that the areas with the most change are in the direction of the open ocean rather than the coast.

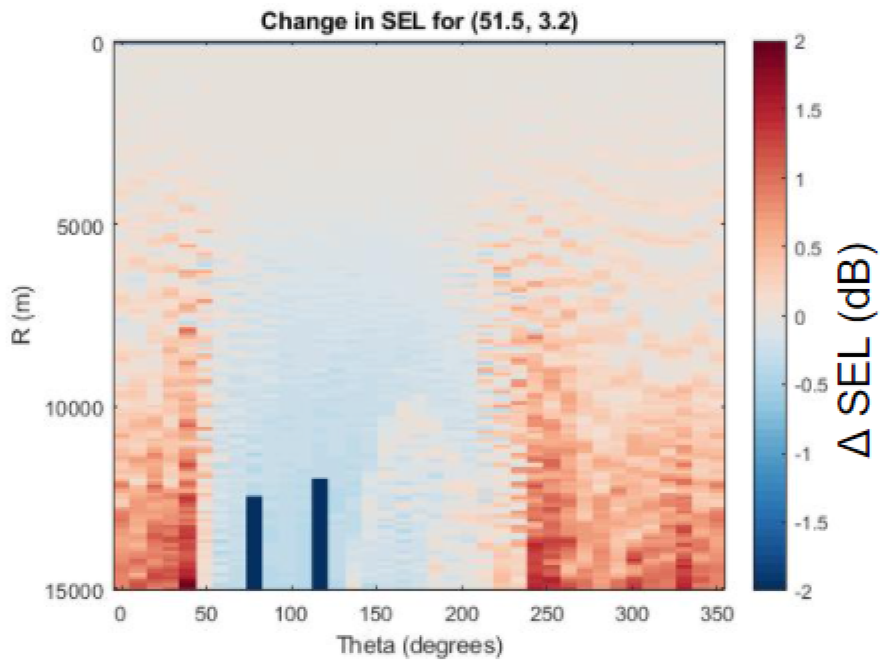


Figure 3.15 Graphical Representation of the Change in Sound Exposure Level (SEL) at (51.5, 3.2)

However, like location 2, the coastal area has a more negative change than the rest of the area, this negative change just happens to be quite a bit less than the positive change apparent in the open ocean section. Although, once averaged out, while the average change is positive, it is still close to zero at 0.253 dB. Even though it is small, it is still the location with the largest positive change at over a factor of 5 larger than locations 4 and 5 and nearly double location 9. The eighth location, shown in Figure 3.16, is the most unique location with the change in SEL varying greatly with both theta and R.

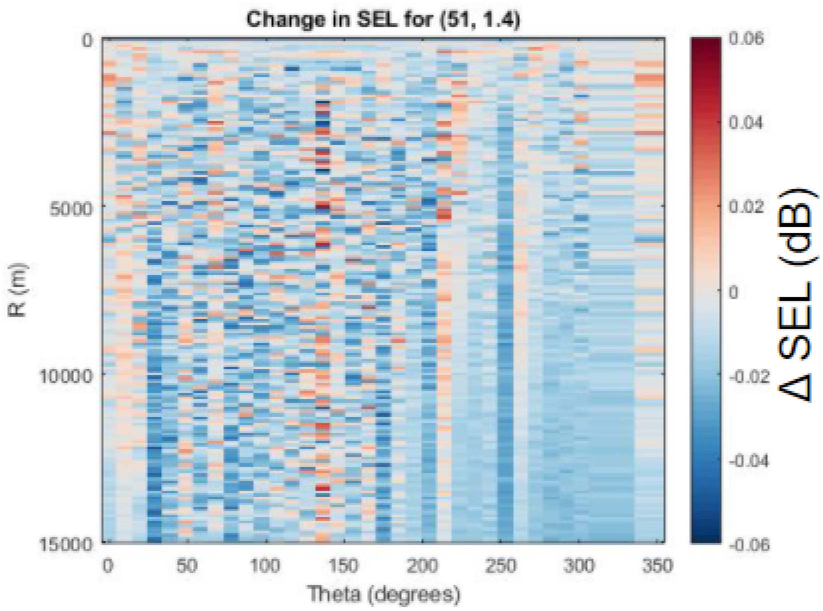


Figure 3.16 Graphical Representation of the Change in Sound Exposure Level (SEL) at (51, 1.4)

This location is in the narrowest strait of all the locations, so this could be a major reason as to why the change in SEL looks so odd. In addition, the changes here are much smaller than in any other location, so while the colours appear very distinct, the values are actually not that different. This location in fact has the smallest absolute change with a decrease of 0.0132 dB. The ninth location, shown in Figure 3.17, is the last positive change location.

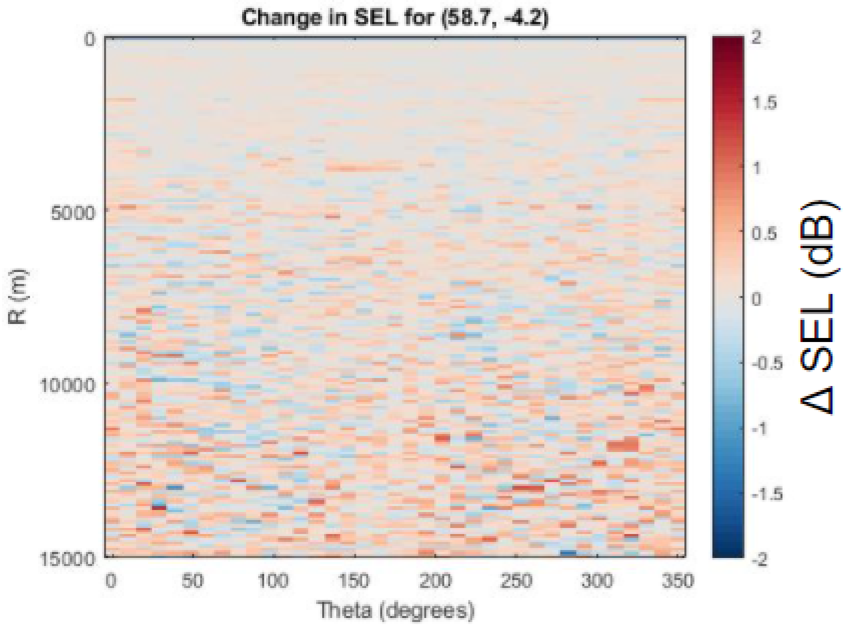


Figure 3.17 Graphical Representation of the Change in Sound Exposure Level (SEL) at (58.7, -4.2)

Unlike the rest of the coastal locations, the coast does not seem to have very much of an impact on the change in SEL here. The change seems to be pretty consistently small and positive, independent of theta. Interestingly, though, the change is R dependent, having larger changes further from the sound source. The average change in this location is 0.137 dB, but there are places past 10 km where the local change is near 1.5 dB. The tenth and final location, shown in Figure 3.18, is very similar to locations 1 and 3 where the shape of the change in SEL mimics the "waves" apparent in the modern day and 2050 simulations.

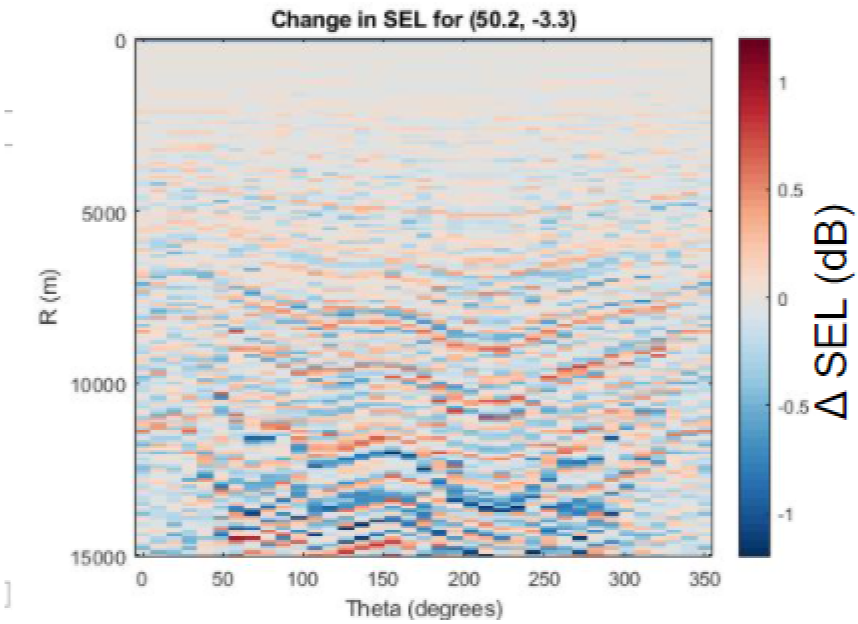


Figure 3.18 Graphical Representation of the Change in Sound Exposure Level (SEL) at (50.2, -3.3)

Again, notice that the colour bar here only ranges from around -1 to 1, so even though the colours appear dark, the changes are quite small. And, although there are places where the SEL decreases by around 1 dB, the average change for this location is only -0.103 dB. This location also (like many of the others) shows significantly larger changes further away from the sound source.

As I've mentioned throughout this section, I calculated an average value for the change in SEL at each location. I took this data and fitted it to a normal distribution PDF shown in Figure 3.19. Keep in mind that this PDF was created with only 9 data points so its accuracy is uncertain.

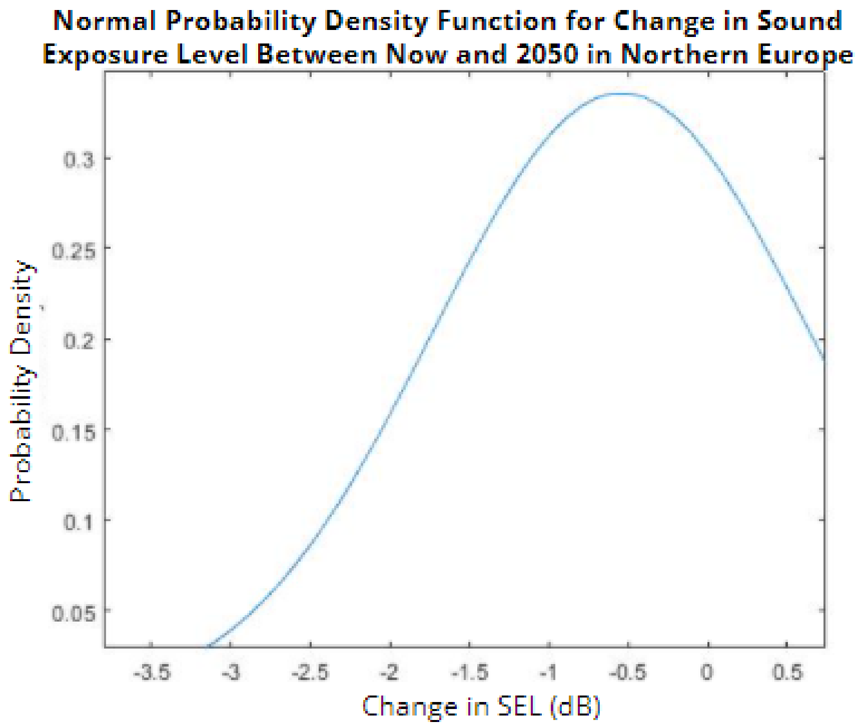


Figure 3.19 Probability Density Function (PDF) from a normal distribution of change in Sound Exposure Level (SEL) data from 9 locations in the Baltic Sea, North Sea, and English Channel

Evidently the probability density is greater for negative changes, but the function is centered close to zero at around -0.5 dB. It's interesting to note that 4 of the locations studied had a positive change and 5 had a negative change. The locations with negative changes just had much larger changes than those with positive values. There were 6 locations with an average absolute change of less than .3 dB. All 4 positive change locations fall in this bucket, and only 2 of the negative ones do. Even so, location 1 definitely skewed the PDF slightly negatively, all of the changes aside from that one are within 1 dB of 0. I included that location's data when solving for the normal distribution because its values are still reasonable and I have no reason to believe there was an error in the simulation runs for that location.

3.3 Discussion of Results

Overall, the initial results of the modern day and 2050 simulations showed an average TL of around 30 dB. All locations had an SEL at the sound source of ~185 dB and their SEL at 15 km ranged from ~145 dB to ~160 dB. Notably, the ocean locations (6, 8, 9, and 10) had an average TL of 35 dB while the brackish locations (1, 2, 3, 4, and 5) had an average TL of 28 dB. As I mentioned briefly above, this is not what I would expect, as the ocean locations are both warmer, and have higher levels of salinity. Refer back to section 1.2 for a more in depth explanation, but increases in either temperature or salinity should lead to decreases in attenuation which should be represented by smaller TL and thus higher SEL. While this discrepancy could be explained by the fact that the attenuation equations I was using were for ocean water, and not brackish water, it could also confirm that changes in the characteristics of water have minimal impacts on the attenuation of sound, especially for low frequency noise such as that produced by tidal turbines. This also suggests that location has a large influence on sound propagation. As I noted in section 3.1 above, the 4 locations present in narrow straits (2, 4, 5, and 8) had the same TL (30 dB) despite varying water characteristics (temperature and salinity).

Now, onto the impacts of climate change on this propagation. I hypothesized that the changes in attenuation would be small, but that they would increase the SEL where temperature played a large role, and decrease the SEL where salinity played a larger role. The changes in attenuation were in fact very small, but they trended towards a decrease in SEL despite temperature being the more dominant change with global climate change. It's also important to note that while the changes should be small simply because water characteristics do not play that large a role in the attenuation of low frequency noise, 2050 is also not very far away, so it would be very surprising to find a large amount of change in only 35 years (2015 - 2050). However, these changes might be larger than it seems at first glance, given the amount of ambient noise in the ocean.

Recall, from section 1.3, tidal turbine noise is typically 35-40 dB above the natural fluctuations in ambient noise between tidal states [16]. A study by C. Bassett et al. (2011) found that ambient noise off the coast of Washington for a range of frequencies between 156 Hz and 30 kHz is around 117 dB exceeding 100 dB 99% of the time [26]. This is consistent with ambient noise levels in the North Sea. A study by the UK Marine Strategy organization (2018) found median noise levels for the 63 Hz band to be 90.5 dB and 93.6 dB for 125 Hz band [27]. Since tidal turbine noise ranges from 25 Hz to 2500 Hz it is fair to say the ambient noise conditions in this frequency range is likely higher than that recorded just for the 63 and 125 Hz-bands from the North Sea study. Assuming ambient mean total sound pressure levels (25 - 2500 Hz) to be ~120 dB and given the maximum locationally specific change being ~ -5 dB (at location 1) climate change could cause changes above ambient conditions of up to 13% in just 35 years. Now, there were only a few places in location 1 that had changes as large as 5 dB and no other locations had changes greater than 4 dB, so having a 13% change above ambient conditions would certainly be rare, but according to this study, it could be possible.

Some other interesting notes from the results include the impact of location on the change in SEL. As I discussed earlier in this section, location has a large impact on sound propagation in general. According to the results in section 3.2, location also has a significant impact on how climate change will affect sound propagation. Locations 1, 2, and 3 which are all in the Baltic Sea showed the most negative change in SEL, while the remaining locations all showed very minimal changes (both positive and negative). In addition, locations 4, 5, and 8 showed the least amount of average change, and all three of these locations were in the narrowest straits. It is also interesting how the change in SEL is influenced by the presence of a cove/ coastline versus open ocean. In all the locations that had both open ocean and coasts nearby the change in SEL showed distinct differences in these two areas. The sections with open ocean showed more positive change, or little change while the areas near the coast showed more negative changes. However, it is important to note that it is possible that this result is due to the lack of echo in the UAS model. Another interesting point is that the sound change became more pronounced further from the sound source. This makes sense, as of course there would be no change at the sound source, and as the sound propagates through the ocean, the small changes in attenuation compound, resulting in relatively larger changes past 10 km with minimal changes before.

3.4 Limitations of the Study

This research was limited to the capabilities of the UAS model. UAS does not include backscatter of energy, so, in the locations where that echo might have had a significant impact on the propagation of the sound, the results are likely inaccurate. In addition, in order to use this software I requested a student license, which did not include any technical support. The code provided with the software to do the post processing of the simulation was filled with bugs. I debugged a lot of the pre and post processing scripts, but there were portions that I could not fix. This led to me writing my own code for many of the figures seen throughout this paper, and all of the ones in sections 3.1 and 3.2. The errors in the provided code not only hindered my ability to graph the data, but they also made some of the data, namely the TL data, unavailable, so I had to solve for that myself as well. On top of these issues, one of the bugs in the code that I could not solve, was the reason I have no results for my 7th location. While the simulation did run for that location, the post processing failed. Another limitation of this study was the use of a default seabed. With more time and resources I would have inputted an accurate seabed for each location, rather than having them all share a simplified seabed. I also would have had the soundsource rest on the seafloor at each location, where tidal turbines usually rest, rather than having it suspended 20 m under the surface everywhere.

This research was also limited in that my hypothesis was based on attenuation for sea water when over half of my locations were in brackish water. While the changes in attenuation were minimal, I would be interested to see if the use of brackish water specific attenuation equations would have significantly changed my hypothesis. Another limit to this research was that I did not have access to data for the pH, so not only was there no change in the pH between modern day and 2050, there was also no change in the pH between each of my locations. I kept the default pH settings, which were for a location in the Baltic Sea at (55.6, 16.9). Since this default location was in the area studied, and since pH has minimal impact on sound attenuation, I doubt this made a large difference, but it is still an important limitation. One of the largest limits to the research exists simply because I chose to use colormaps to view my results. It is quite difficult to accurately pinpoint which color exactly is being shown on the map, and to match that to what is being shown on the color bar. However, while this might not be the most accurate way to determine the exact SEL at any particular point or the exact TL for a certain location, it is useful for comparisons and does give a good general idea for what the results are. In addition, this limit is why I chose to utilize a PDF for my final results based on the actual data from the simulations rather than just using colormaps. Although, the PDF itself is limited as I only had data from 9 locations. On top of that, a lot of the changes at each location were theta and R dependent so the overall average doesnt give the whole picture. However, the colormaps combined with the PDF gives a pretty good view into the results of this study.

4. CONCLUSION

Renewable energy is consistently talked about as one of the best ways to reduce carbon emissions and help stop climate change. Yet, ocean energies are constantly looked over in favour of wind or solar energy. In order for the world to achieve energy independence from fossil fuels, ocean energy is needed to overcome the problems of inconsistency and the intermittent nature of wind and solar energy. In the scientific community, tidal energy has been recognized as an attractive solution and it has been seeing increasing research interest [4]. Even though the potential of tidal energy, and other ocean renewable energy sources, has been acknowledged, the technology is still in its infancy. I believe that in order to fully realize the potential of ocean energy, more studies, like this one, need to be undertaken, to spread information about these amazing devices and hopefully encourage their advancement and use throughout the world.

4.1 Recap of Research

This study was designed to help understand both the ways in which tidal energy might adversely impact its environment, and how climate change might affect those impacts. To narrow this goal, the study focused on the sound created by tidal energy generation. First, I decided where I wanted to study these turbines. I decided on Northern Europe, in the Baltic Sea, North Sea, and English Channel because this is where the bulk of current tidal energy generation is happening. Then, I determined how the marine environment (temperature and salinity) would change over time using 43 coupled CMIP6 global climate models. Next, I found an acoustic simulator, UAS, to run sound propagation models for these tidal turbines. I used Matlab for the pre and post processing of this simulation, then again to display the results and calculate a normally distributed PDF. The simulations aimed to show how sound propagates from a tidal turbine device when it is in use in a variety of different locations both in modern day and in 2050. The PDF aimed to show how sound from a tidal turbine device (or other low frequency broadband sound) could be expected to change as the climate changes.

From the initial simulations I found that as sound propagates from its source, time independent waves can form based on the shape of the sea floor (bathymetry). These waves were apparent in the modern day simulations as well as in the 2050 simulations, and more surprisingly, in the change in SEL maps as well. I also found that the intensity of the sound was greater in the brackish locations than in the pure ocean ones. Overall, this study found that the characteristics of the water, namely temperature and salinity, do not have a large influence on the attenuation of low frequency sounds, like those from tidal turbine devices. However, this study found that location has a relatively large influence on sound propagation.

In regards to the implications of climate change on sound propagation from tidal turbines, this study found that the Sound Exposure Level as emitted from tidal turbine devices, will most probably decrease with climate change. Now, this result does not imply that climate change is good because it reduces one of the environmental impacts from tidal turbine devices. The amount of change was sufficiently small, and the sample size also sufficiently small so that future studies, ones that include backscattering of energy or tidal farms rather than individual turbines for example, might reach a different conclusion. However, within the scope of this research, I can conclude that climate change's impact, while minimal, reduces the intensity of sound that propagates from tidal turbines. Since, of course, like with any other renewable energy, a concern about tidal energy is its impacts on the ecosystem it is placed in, these results suggest that as the oceans warm, the potential impacts of tidal turbine noise will be reduced.

4.2 Broader Impacts

This study was designed to be scalable so the results could be applied to a variety of situations. The findings from this research suggest that propagation of low frequency noises is not easily changed with altered water characteristics. This means that in order to sufficiently reduce the amount of noise produced by some low frequency device underwater, a reduction at the source is necessary. In the example of tidal energy, perhaps combining a tidal energy device with an above water energy storage device or wind turbine, could allow at least some of the noise from the energy generation to be released above water, rather than into the ocean ecosystem. In addition, perhaps this study could encourage a reduction in underwater noise from other sources, such as shipping, weapons, and hydrocarbon exploration. Ideally, as I mentioned above, this study will also stimulate investments into tidal energy research and development, including into the ways in which local coastal / island communities can invest in tidal energy to boost their economy and bolster energy independence. If a small, poor community can provide energy for itself while creating jobs, it has the potential to uplift the entire group, and benefit society as a whole. I also hope to encourage the coupling of energy storage systems (ESSs) with tidal and wave energy devices to maximize their potential.

4.3 Future Work

As I've mentioned throughout this paper, ocean energy is entirely under researched, so there is a lot of potential future work to do in this sector. This study itself could be expanded to different types of marine energy sources, such as different forms of tidal energy converters like tidal kites, or more standard horizontal or vertical axis turbines. It could also expand to wave energy devices or thermal energy converters. On top of this, I would be interested in seeing a study of the sound from an entire tidal or wave farm, rather than from a single turbine. Another interesting extension of this study would be to see even more locations around the world. Possibly in Alaska, near Cook Inlet, or throughout the Aleutian Islands. An expansion of this sort could help create a more certain PDF or could show large differences in different parts of the world. I would also be interested in researching more of the actual impacts of anthropogenic sound on sealife. There is currently research being done by Professor Sarah Henkel at Oregon State University on anthropogenic noise effects on fishes and crabs, but there is so much more to know in this field. As I mentioned earlier in this paper, it would also be beneficial to do research into methods of reducing underwater anthropogenic noise, because knowing how it hurts the environment is only half the battle. On that note though, understanding further environmental impacts of tidal energy is a very important future research topic. Whether that be different ways to reduce ecosystem disturbances or ways to avoid marine animal collisions, it is important to thoroughly understand how tidal energy will impact its surrounding so it can be readily and widely implemented.

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