Kriegers Flak
Offshore Wind Farm

Underwater Noise Modelling
EIA - Technical Report
January 2015

NIRAS

This report is prepared for Energinet.dk as part of the EIA for Kriegers Flak Offshore Wind Farm.

Underwater noise modelling

EIA for Kriegers Flak Offshore Wind Farm

Technical report

January 2015

Prepared by: Mark Aarup Mikaelsen
Controlled by; Esben Tarpgaard
Approved by : Mette Jeppesen

Final version

Table of contents

APPENDICES

Summary

On behalf of Energinet.dk, NIRAS A/S has undertaken underwater noise modelling for pile driving operations during the construction of wind turbines at the Kriegers Flak Offshore Wind Farm, located in the Baltic Sea, 15 km off the coast of Møn.

The construction of offshore wind farms include activities that produce noise levels harmful to nearby marine mammals and fish. The most significant noise levels result from driving monopile foundations into the seabed.

Underwater noise modelling for the pile driving operations was performed for the worst case scenario using the largest proposed monopile diameter of 10 m, with a construction time of 6 hours as specified in the technical project description. Also, modelling is based on only one foundation being installed within any 24 hour period.

The modelling scenarios sought to determine all necessary sound levels to allow for accurate impact assessment of the piling activities. The modelling included determining peak-levels, peak-to-peak levels and sound exposure levels. Furthermore, species specific modelling was carried out, with the results reflecting the actual hearing of relevant species groups.

1 Introduction

The planned Kriegers Flak Offshore Wind Farm (600 MW) is located approximately 15 km off the coast of Møn (Denmark), in the Baltic Sea. The turbine manufacturer and size has not yet been chosen, however the wind turbine sizes will be in the range from 3 MW to 10 MW. The water depth at Kriegers Flak is between 16 m and 25 m.

The purpose of this report is to perform underwater noise modelling to investigate and document the underwater noise levels resulting from construction of the wind farm, to allow for an environmental impact assessment of the effect of underwater noise on marine mammals and fish.

1.1 Project objectives

The objective of this report is:

To use available knowledge about underwater sound propagation to determine the worst case sound exposure in the Baltic Sea as a result of pile driving operations during the construction of the Kriegers Flak Offshore Wind Farm. Modelling will extend to ranges where significant impact on marine mammals can occur.

2 Description of activities

It is not yet decided what foundation type will be used, and therefore the modelling performed in this report is based on the worst case scenario.

The following information is based on (Energinet.dk, 2014).

2.1 Wind Farm layout

As input for the Environmental Impact Assessment (EIA), possible and likely layouts of the offshore wind farm at Kriegers Flak have been assessed and realistic scenarios are used in the EIA. It must be emphasized that the layouts may be altered by the signed developer. Possible park layouts with a 10 MW wind turbine is shown in Figure 1.

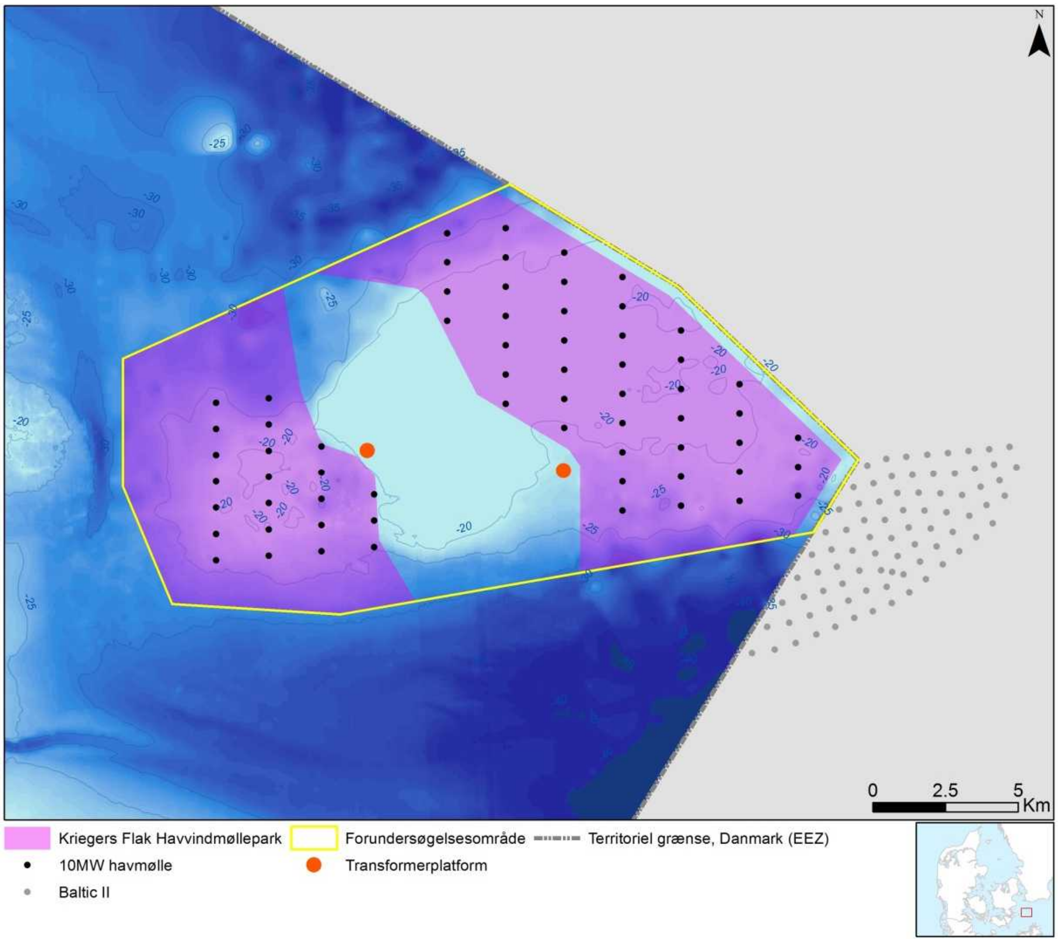


Figure 1: Proposed layout for 10 MW turbines at the eastern and western part of the planned wind farm (purple polygons) at Kriegers Flak at Danish territory. The two red dots indicate the position of the offshore sub-station platforms. The yellow line delineates the pre-investigation area. In the south-eastern part of the map turbines within the German Baltic II OWF are shown.

2.2 Foundation considerations

The foundation types possible for the Kriegers Flak Wind Farm include jacket, gravity and monopile foundations. The worst case scenario is in this project assumed to be the one that causes the highest underwater noise levels.

Gravity foundations consist of a heavy concrete base that is lowered onto the seabed and due to its great weight will remain stable. The installation of these foundations cause very low noise levels and as such are considered irrelevant in a worst case consideration with regards to noise exposure.

Jacket foundations consist of a number (typically 4) piles attached to a metal frame. These piles are positioned like the legs on a chair in each corner of the metal frame, and using impact hammers each pile is driven into the seabed for stability. This action creates very high noise levels as the energy from the hammer makes each pile vibrate and thus create sound waves.

Monopile foundations consist of a single very large diameter steel or concrete pile that is driven into the seabed by an impact hammer. Monopile diameter is considerably larger than for a jacket foundation for the same wind turbine size. The noise level of sound emanating from the vibrating pile is higher than for jacket foundations. The larger the diameter of the monopile, the more force required to drive it into the seabed and thus the higher the source level from the hammer blows.

2.3 Pile driving source level considerations

Based on the above, it was chosen only to model monopile foundations using an impact hammer, as this is assumed to represent the worst-case scenario.

As mentioned earlier, the wind turbine size has yet to be decided, however will be between 3 MW and 10 MW. In order to model the worst case scenario, it was chosen to model the largest turbine size of 10 MW which requires a monopile with a diameter between 8 m – 10 m dependent on local conditions. The modelling will thus, as the worst case scenario only consider 10 m diameter monopiles.

No existing wind farms have used 10 m diameter monopiles of this size to this date, however source level modelling for a 10 m monopile was performed by SubAcoustech for Horns Rev 3 offshore wind farm and in agreement with Energinet.dk should also be used for Kriegers Flak. Here, the source level was determined to be: $SPL_{zero\text{-}peak}$ @ 1 m distance = 244.7 dB re. 1 µPa, and SEL @ 1 m distance = 221.6 dB re. 1 µPa.

Due to the lack of actual source level measurements for this monopile size, it was chosen to use the source levels provided by SubAcoustech.

2.4 Source modelling method

In the technical description report it is written that the impact piling operation per pile is expected to take between 4 – 6 hours (Energinet.dk, 2014). This is supported by (Nedwell, et al., 2012) where a worst case duration was chosen to be 5 hours. The chosen duration for underwater noise modelling will be 6 hours according to agreement with Energinet.dk.

The hammer is proposed to strike with a maximum energy of 3,000 kJ, with 20 strikes per minute, and a maximum of 7,000 strikes during the 6 hours it takes to install a single foundation.

In the technical description report it is furthermore described that only one wind turbine foundation will be installed within a 24 hour period.

The installation of each foundation is split into 3 phases in order to accurately reflect the typical scenario.

2.4.1 Soft start phase

Each pile driving session is begun with a 20 minute soft start phase, where the hammer energy is kept low, at 15% of full hammer energy; 450 kJ.

With low hammer energy follows a reduced source sound level, but still loud enough to scare away any marine mammals in the vicinity of the piling operations. It is assumed that marine mammals will flee from the area with a speed of 1.5 m/s which is considered the average cruising speed for a harbour porpoise mother-calf pair, (Otani, et al., 2000).

The sound propagation modelling includes this fleeing behaviour for the thresholds used for the marine mammal assessment. These include all M-weighted thresholds. Fish however are not expected to flee, and the $SEL_{c,24h}$ thresholds therefore do not include fleeing.

2.4.2 Ramp up phase

After the soft start phase, the energy is slowly increased as the pile is driven further into the sediment layers. Depending on the layers, the ramp up phase will be more or less linear. When the pile reaches a hard layer, more hammer energy is required to drive the pile into the layer. It is therefore very location specific how the ramp up process will occur. In order to model a likely scenario, it is assumed that there will be a linear increase in energy from the 15% of full energy from the soft start phase to full hammer energy.

This phase is set to last 4 hours and 40 minutes.

2.4.3 Full energy phase

Once the ramp up phase completes, the energy is held at 100% for the last hour of pile driving.

It is important to notice, that the described approach attempts to model a representative scenario, and the actual installation of the foundations will deviate from the above in duration and energy increase linearity of phase 2 and 3.

2.5 Summary – chosen source modelling inputs

The method of modelling the activities as described in this chapter, was chosen in cooperation with SubAcoustech and Energinet.dk in order to ensure a similar approach to underwater sound propagation modelling in the two offshore wind farm projects: Kriegers Flak, and Horns Rev III.

Table 1 summarizes the chosen source inputs for the underwater noise modelling.

Parameter	**Value used in modelling**
Wind Turbine size	10 MW
Foundation type	Monopile (d = 10 m)
Hammer force	3,000 kJ
Source Level ($SPL_{zero\text{-}peak}$ @ 1 m)	244.7 dB re 1 µPa
Source Level (SEL @ 1 m)	221.6 dB re 1 µPa
Installation duration per foundation	6 hours
Number of strikes per foundation	7,000
Maximum number of foundations installed within a 24 hour period	1

Table 1: Source modelling parameters.

3 Method

This chapter introduces the relevant units of measurement used to represent the underwater noise modelling results. Following this introduction, the source level is given in the relevant units. Then, underwater sound propagation theory is briefly explored and the methods used by NIRAS' underwater noise propagation software NISIM, are explained.

3.1 Units of measurement

Underwater sound levels are measured in dB re. 1 µPa. Different methods of representing the sound level exist to characterize the intensity, exposure level, max levels along with species specific weighted levels. Depending on the intended use of the results, and the type of source, it can be useful to use one sound level representation over another.

For impulsive sound sources, such as impact piling, and thus of interest in this project, the three metrics used are:

- The sound pressure level peak-peak (SPL_{pp}) and zero-peak (SPL_p)
- The sound exposure level (SEL)
- M-weighted SEL (M_{hf} and M_{pw})

A number of threshold levels using these three metrics have been selected, by the subcontractors in charge of performing the impact assessments for fish and marine mammals respectively, and will thus be modelled and presented in this report.

The three metrics are briefly explained in the following, while the thresholds are explained in the respective assessment reports for fish and marine mammals.

3.1.1 Sound Pressure Level (SPL_p and SPL_{pp})

The SPL_p is the maximum instantaneous sound pressure level of an impulse *p(t)*, given by:

$$SPL_p = 20 \log_{10}(\max|p(t)|)$$

The closely related SPL_{pp} is the maximum difference in sound pressure level of an impulse *p(t)*, given by:

$$SPL_{pp} = 20 \log_{10}\left(\max(p(t)) + \left|\min(p(t))\right|\right)$$

Where SPL_p is usually the instantaneous change in SPL at the occurrence of an impulsive noise from zero dB to the maximum SPL, the SPL_{pp} represent the differential change from positive maximum to negative minimum as a result of the wave propagation. If the pressure wave maximum and minimum are direct opposites, SPL_{pp} will simply be twice as high as SPL_p, that is SPL_p + 6 dB.

3.1.2 Sound Exposure Level (SEL)

The SEL, also known as the sound exposure level is defined as the time-integral of the square pressure over a time window T covering the entire pulse duration, and is given by:

$$SEL = 10 \log_{10}\left(\int_T p^2(t)dt\right)$$

In the case of impulsive sources like impact piling, SEL describes the summation of energy for the entire impulse, and can be expanded to represent the summation of energy from multiple pulses. The latter is written SEL_C denoting that it represents the cumulative sound exposure. The sound exposure level is often used in the assessment of marine mammal and fish behaviour over an extended duration of impulsive sources, or for multiple concurrent sources.

3.1.3 M-weighted SEL

The M-weighted SEL adapts the SEL modelling to reflect the hearing of a certain species or group of species with similar hearing ability. M-weighting functions can be thought of as the waters counterpart to the A-weighting function which is often used to represent the hearing of humans in air. These weighting functions take into account the nonlinear hearing of the species by a set of correction coefficients at each frequency. Thus, the results represent what the species will actually hear when exposed to a certain noise. The M-weighting functions are therefore very useful when determining the behavioural responses of marine mammals to any noise.

In this project, the two marine mammal groups of interest are: High frequency cetaceans and pinnipeds.

M_{hf} is the M-weighting correction for high-frequency cetaceans while M_{pw} is the M-weighting correction for pinnipeds in water.

3.2 Noise modelling criteria

To assess the impact on marine mammals and fish, it was chosen by DHI and BioApp that the threshold levels in Table 2 should be modelled.

Criteria	**Effect**	**Single strike**	**Multiple strikes**
SPL_{pp} = 226 dB re 1 µPa	TTS (pinnipeds in water)	X	
SPL_{p} = 230 dB re 1 µPa	PTS (high frequency cetaceans)	X	
SPL_{p} = 224 dB re 1 µPa	TTS (high frequency cetaceans)	X	
SPL_{p} = 218 dB re 1 µPa	PTS (pinnipeds in water)	X	
SPL_{p} = 212 dB re 1 µPa	TTS (pinnipeds in water)	X	
$SEL(M_{hf})$ = 198 dB re 1 $\mu Pa^2 s$	PTS (high frequency cetaceans)	X	X
$SEL(M_{hf})$ = 183 dB re 1 $\mu Pa^2 s$	TTS (high frequency cetaceans)	X	X
$SEL(M_{pw})$ = 186 dB re 1 $\mu Pa^2 s$	PTS (pinnipeds in water)	X	X
$SEL(M_{pw})$ = 171 dB re 1 $\mu Pa^2 s$	TTS (pinnipeds in water)	X	X
SEL = 164 dB re 1 $\mu Pa^2 s$	TTS (harbour porpoise)	X	
SEL = 213 dB re 1 $\mu Pa^2 s$	Non-auditory tissue damage(fish)		X
SEL = 189 dB re 1 $\mu Pa^2 s$	Auditory tissue damage (fish – hearing generalist)		X
SEL = 185 dB re 1 $\mu Pa^2 s$	TTS (fish – hearing generalist), Auditory tissue damage (fish – hearing specialist)		X
SEL = 183 dB re 1 $\mu Pa^2 s$	TTS (fish – hearing specialist)		X

Table 2: Noise modelling criteria. Thresholds for noise levels chosen for modelling by DHI and BioApp. PTS stands for Permanent Threshold Shift, while TTS means Temporary Threshold Shifts.

For further explanation of the chosen parameters, the reader is referred to the respective reports for the impact assessment for fish and marine mammals.

3.3 Underwater sound propagation

This section is based on (Jensen, et al., 2011) chapter 1 and chapter 3 as well as (Porter, 2011), and seeks to provide a brief introduction to sound propagation in oceans. The interested reader is referred to (Jensen, et al., 2011) chapter 1, for a more detailed and thorough explanation of underwater sound propagation theory.

In the ocean, the sound pressure level generally decreases with increasing distance from the source. However, many parameters influence the propagation and makes it a complex process.

The speed of sound in the ocean, and thus the sound propagation, is a function of first and foremost pressure, salinity and temperature, all of which are dependent on depth and the climate above the ocean and as such are very location dependent.

The theory behind the sound propagation is not the topic of this report, however it is worth mentioning one aspect of the sound speed profile importance.

Snell's law states that:

$$\frac{\cos(\theta)}{c} = constant$$

Where θ is the ray angle, and c is the speed of sound [m/s], thus implying that sound bends toward regions of low sound speed (Jensen, et al., 2011). The implications for sound in water are, that sound that enters a low velocity layer in the water column can get trapped there. This results in the sound being able to travel far with very low sound transmission loss.

When a low velocity layer occurs near the sea surface, with sound speeds increasing with depth, it is referred to, as an upward refraction. This causes the sound waves to be reflected by sea surface more than by the seabed. As the sea surface is often modelled as a calm water scenario (no waves), it causes little to no transmission loss. This scenario will always be the worst case situation in terms of sound transmission loss.

When a high velocity layer occurs near the sea surface with the sound speed decreasing with depth, it is referred to, as a downward refraction. This causes the sound waves to be angled towards the seabed rather than the sea surface, and it will thus be the absorption and reflection of the seabed that determines the transmission loss.

In any general scenario, the upward refraction scenario will cause the lowest sound transmission loss and thus be considered worst case.

The physical properties of the sea surface and the seabed further affect the sound propagation by reflecting, absorbing and scattering the sound waves. Roughness, density and media sound speed are among the surface/seabed properties that define how the sound propagation is affected by the boundaries.

The sea surface state is affected mainly by the climate above the water. The bigger the waves, the more rough the sea surface, and in turn, the bigger the transmission loss from sound waves hitting the sea surface. In calm seas, the sea surface acts as a very reflective medium with very low sound absorption. In rough seas, the sound waves will to a higher degree be reflected backwards toward the source location, and thus result in an increased transmission loss.

Another parameter that has influence on especially the high frequency transmission loss over distance is the volume attenuation, defined as an absorption coefficient reliant on chemical conditions of the water column. This parameter has been approximated by:

$$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 3.0 \times 10^{-4} f^2 \qquad (dB/km)$$

Where f is the frequency of the wave in kHz (Jensen, et al., 2011).

3.4 Underwater noise modelling software - NISIM

NIRAS uses the underwater noise modelling software: NISIM, developed by Heat, Light and Sound Research Inc., by Michael Porter and Laurel Henderson.

NISIM has been developed to model the sound propagation of especially but not limited to impulsive sound sources such as impact piling and seismic surveys.

It uses a fully range-dependent and modified implementation of a ray theory method; "Bellhop" (Bucker & Porter, 1986), (Bucker & Porter, 1987), (Porter & Liu, 1994) and is suited for both shallow and deep water modelling. The implementation was modified to overcome inherited shortcomings of the original Bellhop when it comes to low frequency modelling in shallow water scenarios.

NISIM is able to provide all relevant outputs, including the units of measurement presented in section 3.1. Results are presented in table form as the range from source position to any desired noise level threshold, and in color-coded maps that show the noise levels at any position within a set radius of the source. NISIM uses the acoustic time-series of the actual noise source as input, and thus contains and models the full frequency content of the noise source. NISIM also allows the use of moving sources, as well as stationary sources with a set duration.

NISIM uses a variety of databases to extract the necessary location specific data, such as sound speed profiles, bathymetry, sea state profiles and sediment properties, and will always select the database with the most precise data for the area in question. For this project, it was chosen to define the sediment properties manually as a seabed survey was performed prior to the environmental assessment for the wind farm.

4 Baseline

This chapter describes the baseline conditions at Kriegers Flak, relevant to the underwater noise modelling. This includes seabed sediment type, bathymetry and sound speed profile.

4.1 Bathymetry

NISIM allows the use of either ETOPO-1 by the National Geophysical Data Center under the American NOAA (Amante & Eakins, 2009), or through manual input.

ETOPO-1 is a 1 arc-minute model and consist of data from a number of regional and global data sets. NISIM uses ETOPO-1 by default.

For this project, a finer resolution of 30 arc-seconds was extracted from NOAA's seabed sampling (NGDC, 2013).

4.2 Sound Speed Profile (SSP)

NISIM allows the use of either sound speed profiles from the World Ocean Atlas from 2009 (WOA09), (Locarnini, et al., 2010), (Antonov, et al., 2010), or through manual input. WOA09 is an objectively analysed 1° resolution database including more than 20 parameters, the relevant ones being temperature, pressure and salinity, all given in annual, seasonal and monthly averages, based on historical data. Since the sound speed profile is a function of temperature, pressure and salinity, this database can be used to calculate the sound speed profile.

This database was used for the calculations due to the availability of all relevant parameters for calculating the sound speed profile, and due to being a widely used and maintained database.

It has not been specified at what time of year the construction phase will take place, and the WOA09 database was examined at the Kriegers Flak site for the worst case sound speed profile. It was determined that February would be the worst case scenario, having a strong upward refraction and thus allowing the sound to have very low transmission loss over distance.

Examples of the Sound Speed Profile in the Kriegers Flak area and surrounding Baltic Sea is given in Figure 2.

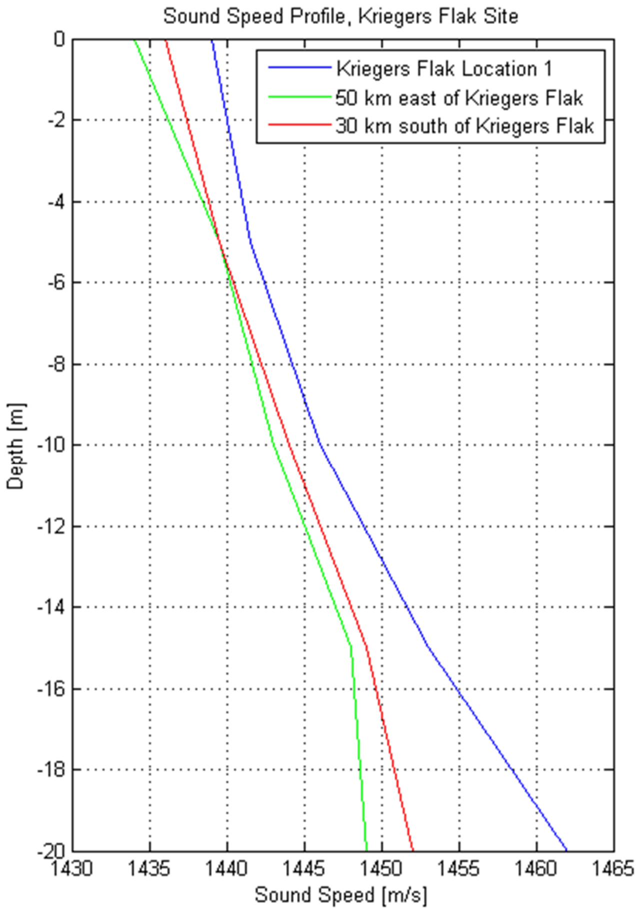


Figure 2: SSP examples for Kriegers Flak. Extracted from WOA09-February.

4.3 Sea surface state

NISIM allows for various sea state modelling techniques, to reflect either calm or any degree of rough seas. As explained in chapter 0, the worst case scenario is calm seas, as it is the most reflective scenario with the lowest transmission loss, and it was therefore the choice of sea surface for this modelling.

4.4 Seabed Layers

The seabed usually consist of different layers of material, the combination and thickness of which has great influence on the sound propagation. This holds true especially for shallow water scenarios as the waves bounce between sea surface and seabed. By default, NISIM uses dbSEABED database by Institute for Arctic and Alpine Research, University of Colorado at Boulder (Halpern & et., 2008). There is however also the option to use a more detailed seabed profile by manually entering it into the model.

As detailed site specific seabed sampling was performed prior to the project, the different layer thickness and types are known, and it was therefore chosen to use these in the model.

An example of the seabed layers at the Kriegers Flak site, is a 2 m sand layer on top of 18 m of Moraine, with a chalk layer below.

4.5 Background noise

There will be several sources of noise not included in the underwater sound propagation modelling. These are:

- Any biological sources, such as marine mammals.
- Noise from ships, as these are expected to produce underwater noise levels inferior to those of the impact piling.

4.6 Summary – chosen inputs

Input parameter	**Value used in modelling**
Sound Speed Profile	February (WOA09)
Bathymetry	30 arc-second extract from NOAA
Sea surface state	Calm waters
Seabed layers	2 m sand on 18 m moraine on chalk
Modelling tool	NISIM
Modelling distance, R_{max}	100 km

5 Construction phase

This chapter provides an overview of the proposed layout of Kriegers Flak Wind Farm (10 MW turbines), and selects a number of representative locations from where the noise exposure is modelled. Tables provide the modelling results by the minimum distances each species must be from the piling operations at the onset of soft-start, in order to receive a total SEL_C below the given thresholds.

5.1 Kriegers Flak site

The offshore wind turbine site at Kriegers Flak is shown in Figure 3, with the wind turbine locations selected for noise modelling marked by yellow circles. The three marked locations were chosen due to being the ones closest to the surrounding countries coasts. There has been minor changes of a few turbine positions in the eastern part of the wind farm area since the modelling was performed. However these changes are not expected to give rise to significant changes of the results of the modelling.

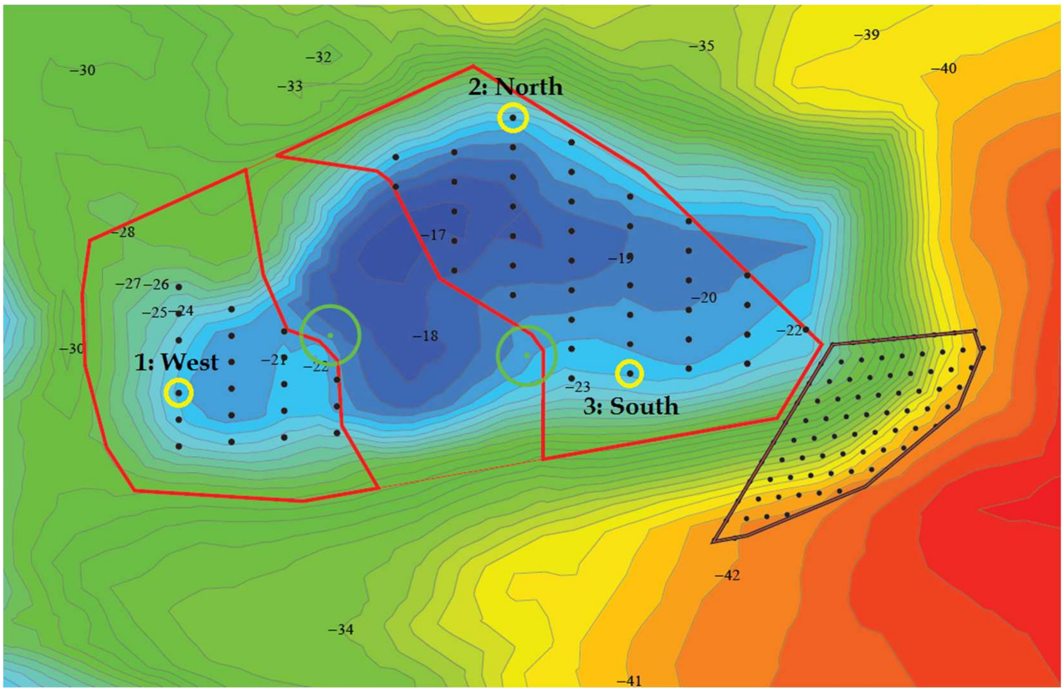


Figure 3: Kriegers Flak Wind Farm layout using 10 MW wind turbines. The yellow circles represent the 3 chosen locations for modelling. The brown area to the east show the German offshore wind farm Baltic II.

5.2 Modelling results

Results from the underwater noise modelling, are given in a combination of tables and sound level maps. Distances in the tables are given in meters from source location. R_{max} indicates the maximum distance at which the sound level can be present in any direction from the source. R_{mean} indicates the average distance from source at which the sound level can be present. If R_{max} for e.g. SPL_p = 220 dB re. 1 µPa is 25 m, it means that sound levels of 220 dB and above will only occur within 25 m of the source, and that beyond that distance, noise levels will be below 220 dB. Sound level maps for SPL_p, SEL and M-weighted SEL are presented in appendices to this report.

5.2.1 Single pile strike results

Single strike SPL and SEL modelling results are given in Table 3, for the three chosen locations.

Distance to thresholds, single strike						
	Location 1: West		Location 2: North		Location 3: South	
Threshold	R_{max} (m)	R_{mean} (m)	R_{max} (m)	R_{mean} (m)	R_{max} (m)	R_{mean} (m)
Peak-Peak Sound Pressure Level - SPLp-p [dB re. 1 µPa]						
226 dB	40	34	38	34	37	32
Peak Sound Pressure Level - SPLp [dB re. 1 µPa]						
230 dB	14	11	13	10	12	< 10
224 dB	29	26	28	25	29	26
218 dB	84	78	80	76	82	78
212 dB	428	375	430	368	412	361
M-weighted Sound Exposure Level - SEL(M_{hf}) [dB re. 1 µPa^2 · s]						
198 dB	< 10	< 10	< 10	< 10	< 10	< 10
183 dB	46	38	47	42	48	43
M-weighted Sound Exposure Level - SEL(M_{pw}) [dB re. 1 µPa^2 · s]						
186 dB	374	355	368	354	328	315
171 dB	2 140	1 790	2 080	1 775	2 045	1 750
Sound Exposure Level - SEL [dB re. 1 µPa^2 · s]						
164 dB	5 160	4 350	5 360	4 160	5 180	4 720
140 dB	96 540	71 200	94 430	70 160	89 920	76 610

Table 3: Single pile strike threshold results.

5.2.2 Cumulative pile strikes results

Cumulative strike SPL and SEL modelling results for the full piling duration of 6 hours and 7000 strikes are given in Table 4, for the three chosen locations.

Distance to thresholds, full piling duration (7000 strikes)						
	Location 1: West		Location 2: North		Location 3: South	
Threshold	R_{max} (m)	R_{mean} (m)	R_{max} (m)	R_{mean} (m)	R_{max} (m)	R_{mean} (m)
M-weighted Sound Exposure Level - SEL(M_{hf}) [dB re. 1 μPa^2 · s]						
198 dB	98	73	91	75	89	67
183 dB	680	600	620	600	720	605
M-weighted Sound Exposure Level - SEL(M_{pw}) [dB re. 1 μPa^2 · s]						
186 dB	13 800	11 500	14 300	11 600	13 600	11 400
171 dB	67 500	64 200	65 000	61 700	65 500	61 900
Sound Exposure Level - SEL [dB re. 1 μPa^2 · s]						
213 dB	1 420	1 100	1 340	1 120	1 590	1 200
189 dB	24 190	20 160	23 400	20 040	25 990	22 150
185 dB	50 400	28 800	50 150	29 050	54 030	44 350
183 dB	56 450	44 350	55 650	42 780	59 670	48 380

Table 4: Cumulative pile strike threshold results.

6 Operation phase

Noise sources in the operation phase is limited to the noise from the operational turbines. This noise can radiate through the foundation and into the water.

Previous assessments for Rødsand Offshore Wind Farm (Tougaard & Teilmann, 2007), Anholt Offshore Wind Farm (DHI, Energinet.dk, 2009) and Sprogø Offshore Wind Farm (Sveegaard, et al., 2008) indicate that operational noise under the water surface from wind turbines will be limited. All reports indicate operational source noise levels 10 – 20 dB above background noise levels in the area, and well below any thresholds for disturbance to occur.

Noise from the operation phase was not modelled in this report as no significant noise is expected. This topic is however further elaborated on in the respective assessments for fish and marine mammals.

7 Decommissioning

It is unclear how any decommissioning would take place in case the wind farm should be demolished in the future. It is however expected that any noisy activities in the case of decommissioning will not exceed those of the construction phase.

Due to the uncertainties of which activities and methods might occur during a possible decommissioning phase, it was not deemed possible nor relevant to model the noise.

8 Cumulative effects

Several activities during the construction phase will have source levels above the background noise in the Baltic Sea. The primary noise source will be the impact piling activity, whereas activities such as ship traffic and cable installation are expected to introduce significantly lower levels of noise

The cumulative effects from ships and cable installation have not been part of the noise modelling documented in this report.

9 Noise Attenuating Measures

In addition to the modelling scenario presented in chapter 5, an additional modelling scenario was agreed with Energinet.dk. The purpose of this scenario, is to determine the effect on threshold distance, when a source level attenuating measure is applied.

This chapter lists source level attenuations obtained with different methods in previous projects, and based on this list, an attenuation level is chosen for the scenario. The choice of an attenuation level is done in cooperation with Energinet.dk.

9.1 Source level attenuating measures

In order to choose a reasonable attenuation level for the scenario, (Reinhall & Dahl, 2011) (Tobias Verfuß, 2012) were studied. The list below comprises the attenuations reported in this literature.

- Temporary noise attenuation pile (TNAP): reduction ≈10 dB
- Big bubble curtain at FINO-3: reduction ≈12 dB
- Big bubble curtain at OWF Borkum West II: reduction ≈5 - 13 dB
- Small bubble curtain at OWF alpha ventus: reduction ≈2 - 13 dB
- Cofferdam at Aarhus Bay test setup ≈22 dB

Based on the above, it was decided and agreed with Energinet.dk to proceed using a cautious 8 dB attenuation level for the scenario.

9.2 Results

9.2.1 Single pile strike results

Single strike SPL and SEL modelling results are given in Table 5, for the three chosen locations.

Distance to thresholds, single strike, 8 dB Attenuation						
	Location 1: West		Location 2: North		Location 3: South	
Threshold	R_{max} (m)	R_{mean} (m)	R_{max} (m)	R_{mean} (m)	R_{max} (m)	R_{mean} (m)
Peak-Peak Sound Pressure Level - SPLp-p [dB re. 1 µPa]						
226 dB	< 10	< 10	< 10	< 10	11	< 10
Peak Sound Pressure Level - SPLp [dB re. 1 µPa]						
230 dB	< 10	< 10	< 10	< 10	< 10	< 10
224 dB	< 10	< 10	< 10	< 10	< 10	< 10
218 dB	22	18	23	18	22	18
212 dB	70	63	68	61	69	66
M-weighted Sound Exposure Level - SEL(M_{hf}) [dB re. 1 µPa^2 · s]						
198 dB	< 10	< 10	< 10	< 10	< 10	< 10
183 dB	< 10	< 10	12	10	<10	<10
M-weighted Sound Exposure Level - SEL(M_{pw}) [dB re. 1 µPa^2 · s]						
186 dB	38	32	40	36	40	33
171 dB	780	712	774	712	762	701
Sound Exposure Level - SEL [dB re. 1 µPa^2 · s]						
164 dB	2 280	1 970	2 340	2 120	2 300	2 050
140 dB	50 800	28 220	50 640	32 260	47 180	29 050

Table 5: Single pile strike threshold results (with 8 dB source level attenuation).

9.2.2 Cumulative pile strikes results

Cumulative strike SPL and SEL modelling results for the full piling duration of 6 hours and 7000 strikes are given in Table 6, for the three chosen locations.

Distance to thresholds, full piling duration (7000 strikes), 8 dB Attenuation						
	Location 1: West		Location 2: North		Location 3: South	
Threshold	R_{max} (m)	R_{mean} (m)	R_{max} (m)	R_{mean} (m)	R_{max} (m)	R_{mean} (m)
M-weighted Sound Exposure Level - SEL(M_{hf}) [dB re. 1 µ$Pa^2 \cdot s$]						
198 dB	30	28	31	28	29	27
183 dB	230	200	225	200	260	210
M-weighted Sound Exposure Level - SEL(M_{pw}) [dB re. 1 µ$Pa^2 \cdot s$]						
186 dB	1 810	1 520	1 770	1 500	1 650	1 600
171 dB	40 200	37 500	40 500	36 200	36 000	34 100
Sound Exposure Level - SEL [dB re. 1 µ$Pa^2 \cdot s$]						
213 dB	385	352	420	384	382	340
189 dB	7 260	5 650	7 300	6 050	6 450	6 100
185 dB	12 090	10 880	14 190	11 290	20 030	11 690
183 dB	18 550	16 130	18 950	16 240	20 160	16 510

Table 6: Cumulative pile strike threshold results (with 8 dB source level attenuation).

10 Possible missing information, that can affect the modelling

The input data used for the modelling is largely based on historical measurements for the region. This will always introduce a level of uncertainty, as deviations from year to year can occur. In the modelling however, all chosen inputs were worst-case scenario data, and it is therefore expected, that if any deviation from the modeled results, it will show lower overall sound levels than modeled.

11 References

Amante, C. & Eakins, B. W., 2009. *ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis..* s.l.:s.n.

Antonov, J. I. et al., 2010. *World Ocean Atlas 2009 Volume 2: Salinity. S. Levitus.* D.C.(Washington): U.S. Government Printing Office.

Bucker, H. P. & Porter, M. B., 1986. *Gaussian Beams and 3-D Bottom Interacting Systems.* New York: Plenum Press.

Bucker, H. P. & Porter, M. B., 1987. *Gaussian Beam Tracing for Computing Ocean Acoustic Fields.* s.l.:s.n.

Chapman, C. J. & Hawkins, A. D., 1973. *A field study of hearing in the cod, Gadus morhua.* s.l.:s.n.

Chapman, C. J. & Sand, O., 1974. *Field studies of hearing in two species of flatfish Pleuronectes platessa (L.) and Limanda limanda (L.) (Family Pluronectidae).* s.l.:s.n.

DHI, Energinet.dk, 2009. *Anholt Offshore Wind Farm.* s.l.:s.n.

Energinet.dk, 2014. *Kriegers Flak Tecnhical Project description for the large scale offshore wind farm (600 MW) at Kriegers Flak.23 September 2014..* s.l.:s.n.

Enger, P. S. & Andersen, R. A., 1967. *An electrophysiological field study of hearing in fish.* s.l.:s.n.

Halpern & et., a., 2008. *Seabed from NCEAS conversion of dbSEABED into "hard" and "soft" bottom types.* s.l.:s.n.

Hawkins, A. D. & Johnstone, A. D. F., 1978. *The hearing of the Atlantic salmon, Salmo salar.* s.l.:s.n.

Jensen, F. B., Kuperman, W. A., Porter, M. B. & Schmidt, H., 2011. *Computational Ocean Acoustics, 2nd edition.* s.l.:Springer.

Locarnini, R. A. et al., 2010. *World Ocean Atlas 2009, Volume 1:Temperature. S. Levitus.* D.C.(Washington): U.S. Government Printing Office.

Nedwell, J. R., Barham, R. J. & Mason, T. I., 2012. *Modelling of Noise during Impact Piling Operations at the Westermost Rough Offshore Wind Farm.* s.l.:s.n.

Nedwell, J. R. et al., 2007. *A Validation of the dBht as a Measure of the Behavioural and Auditory Effects of Underwater Noise.* s.l.:s.n.

NGDC, 2013. *National Geographical Data Center Grid Extract.* s.l.:NOAA.

Otani, S., Naito, Y., Kato, A. & Kawamura, A., 2000. *Diving behaviour and swimming speed for free-ranging harbour porpoise, Phocean phocena..* s.l.:Marine Mammal Science, I6(4), pp. 811-814.

Porter, M., 2011. *The BELLHOP Manual and User's Guide: PRELIMINARY DRAFT.* s.l.:Heat, Light and Sound Research Inc. La Jolla, CA, USA.

Porter, M. B. & Liu, Y., 1994. *Finite-Element Ray Tracing.* s.l.:s.n.

Reinhall, P. & Dahl, P., 2011. *An investigation of underwater sound propagation from pile driving.* Seattle: Washington State Transportation Center (TRAC).

Sveegaard, S., Tougaard, J. & Teilmann, J., 2008. *Sprogø Wind Farm.* Roskilde: NERI Commissioned Report to Sund&Bælt.

Tobias Verfuß, P. J., 2012. *Noise Mitigation Measures & Low-noise Foundation Concepts - State of the Art.* Stralsund: Powerpoint presentation.

Tougaard, J. & Teilmann, J., 2007. *Rødsand 2 Offshore Wind Farm.* Roskilde: NERI Commissioned Report to DONG Energy.

NIRAS

Energinet.dk

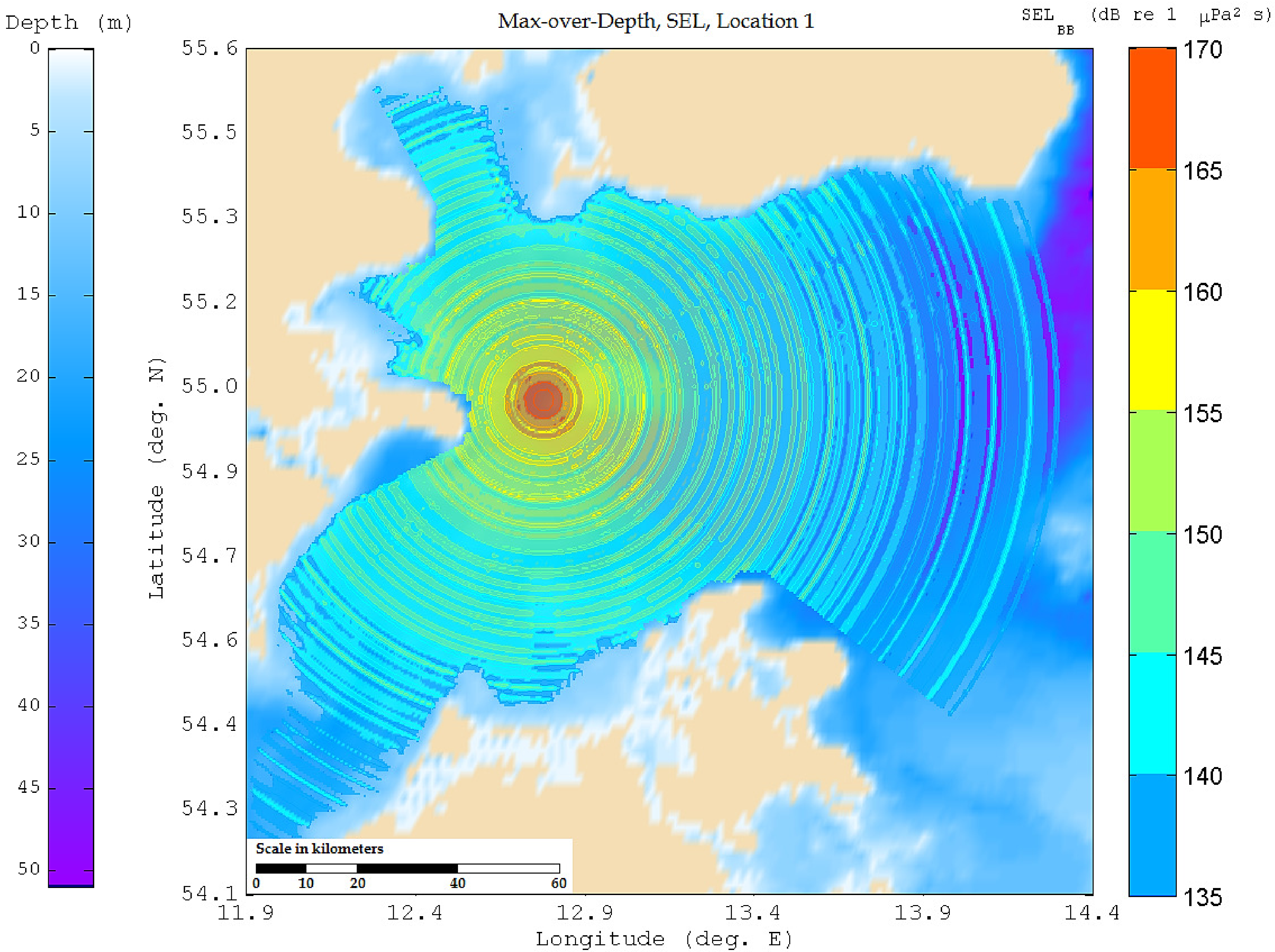
APPENDIX 1:
Sound Pressure Level and Sound Exposure Level maps

- SEL
- $SPL_{zero\text{-}peak}$ J

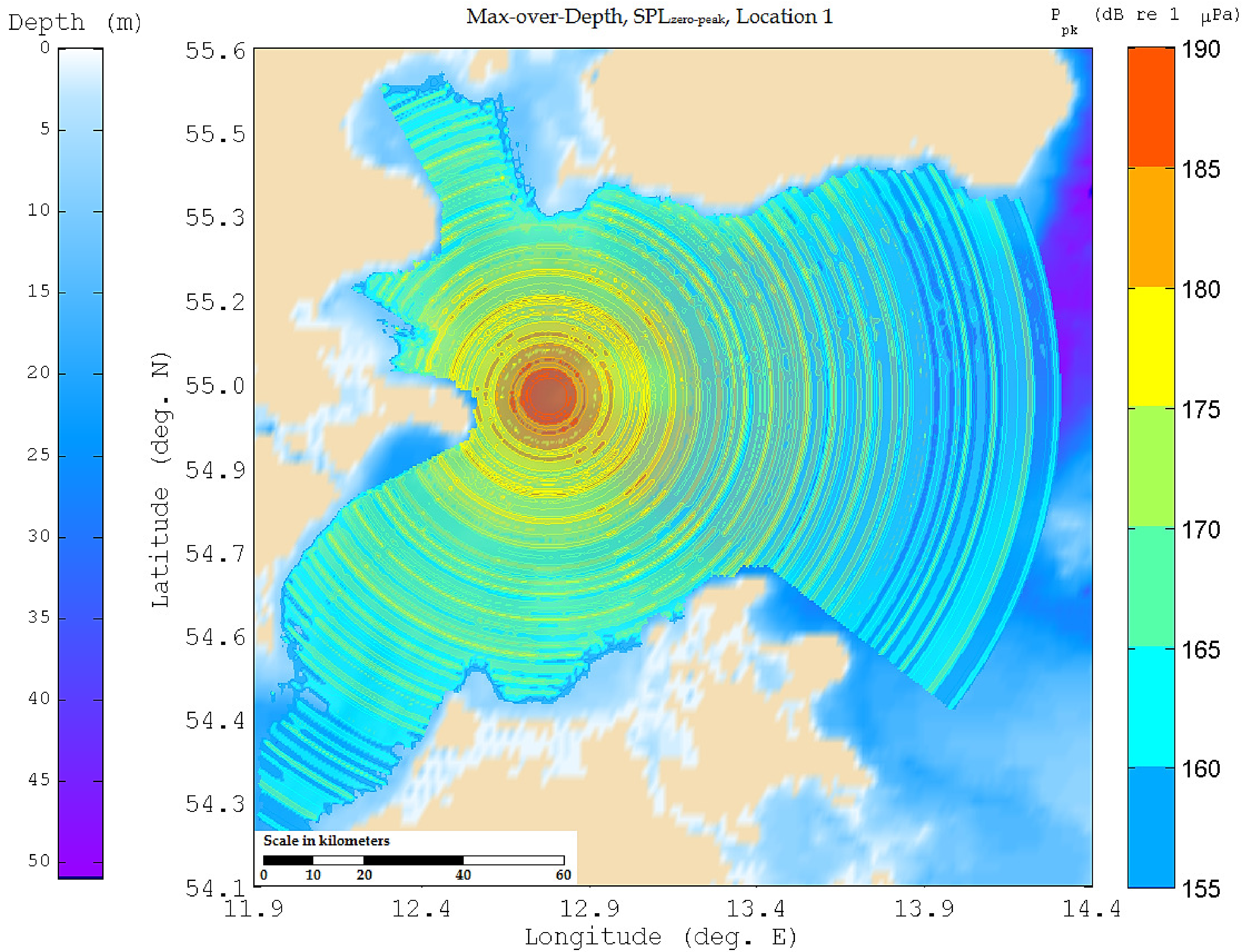
January 2015

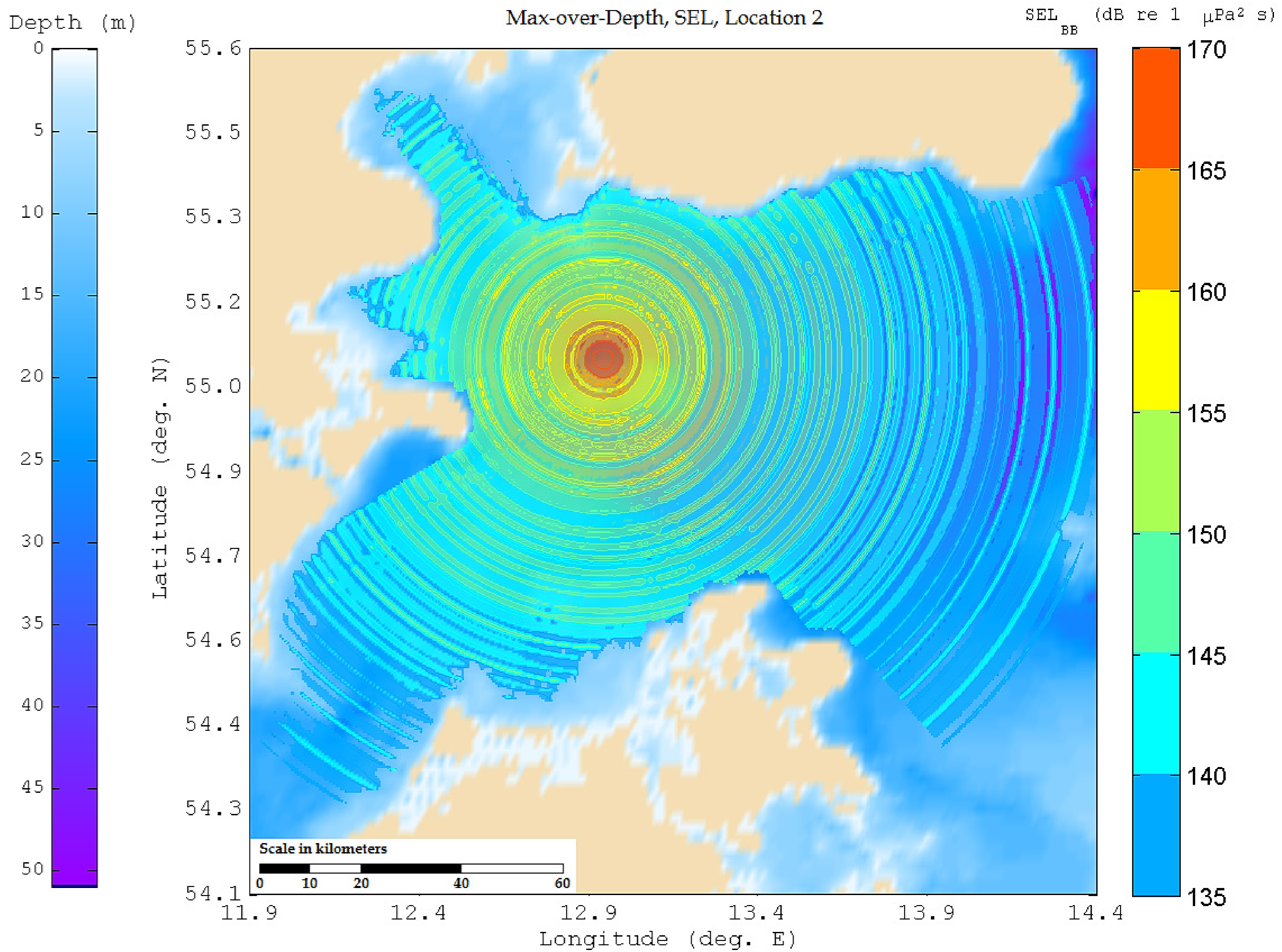
KRIEGERS FLAK OFFSHORE WIND FARM

Underwater sound propagation for impact piling operations during construction phase

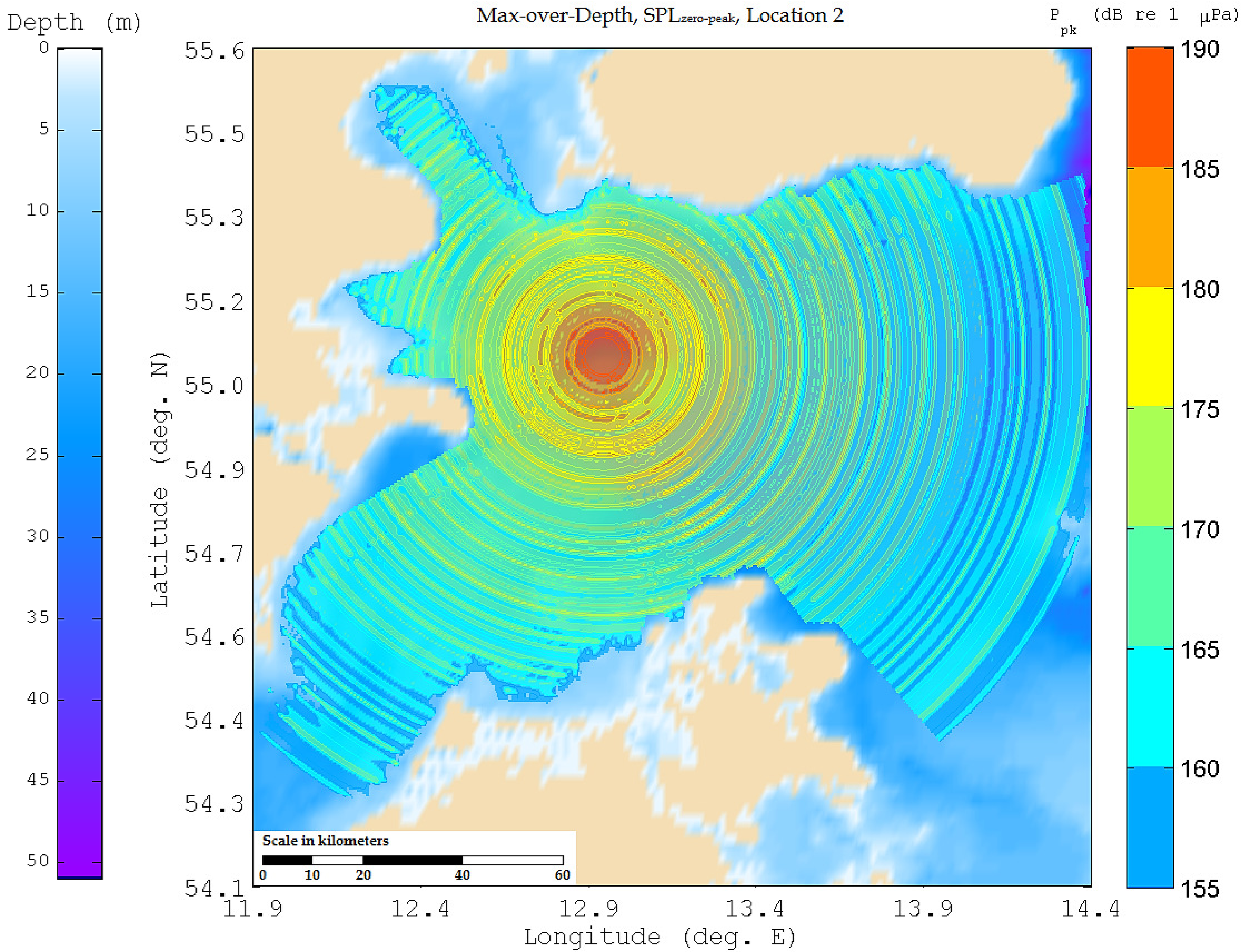


Max-over-Depth, SEL, Location 1
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
SEL BB (dB re 1 µPa² s)
170
165
160
155
150
145
140
135

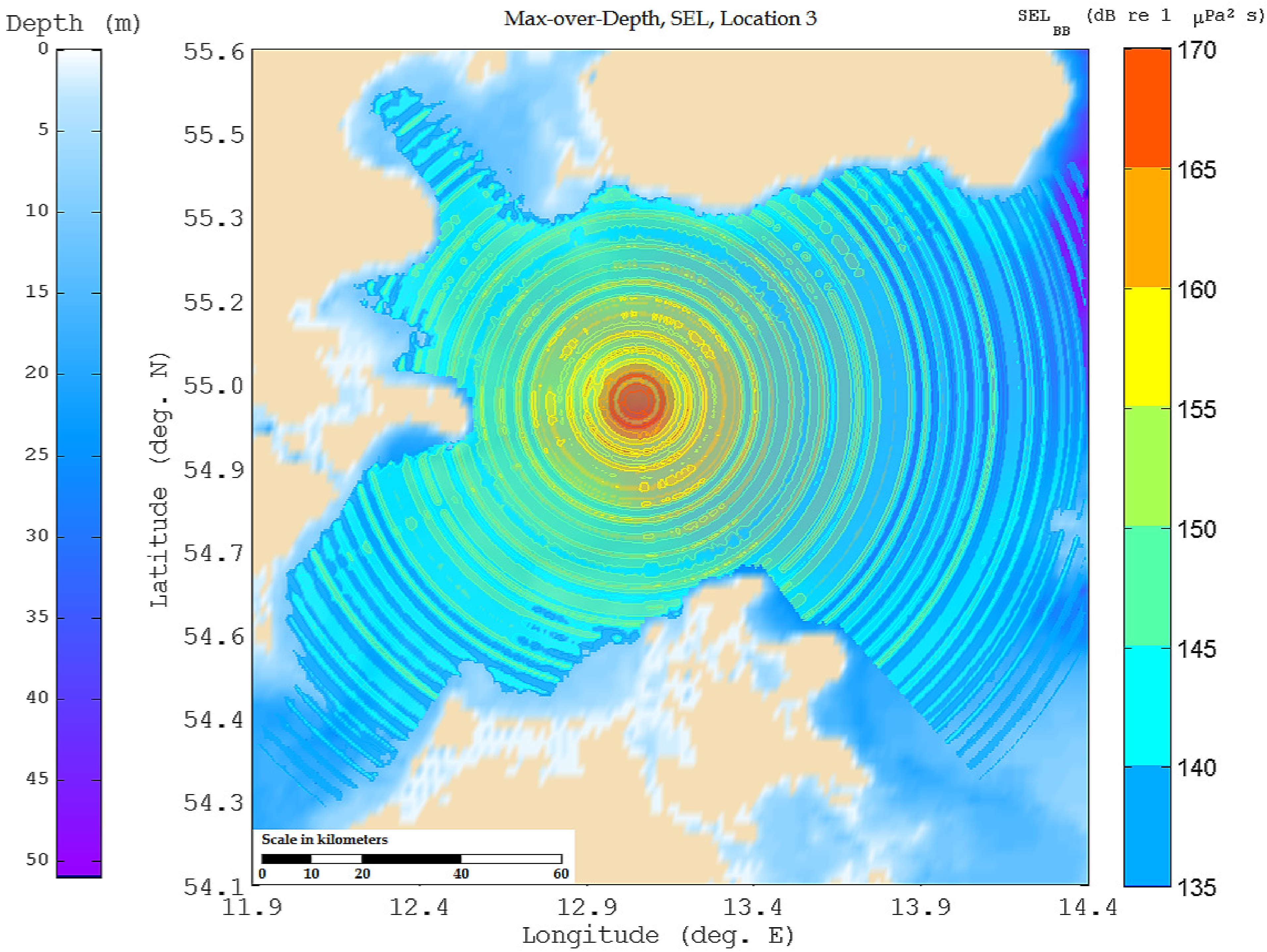

Max-over-Depth, SPLzero-peak, Location 1
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
Ppk (dB re 1 µPa)
190
185
180
175
170
165
160
155

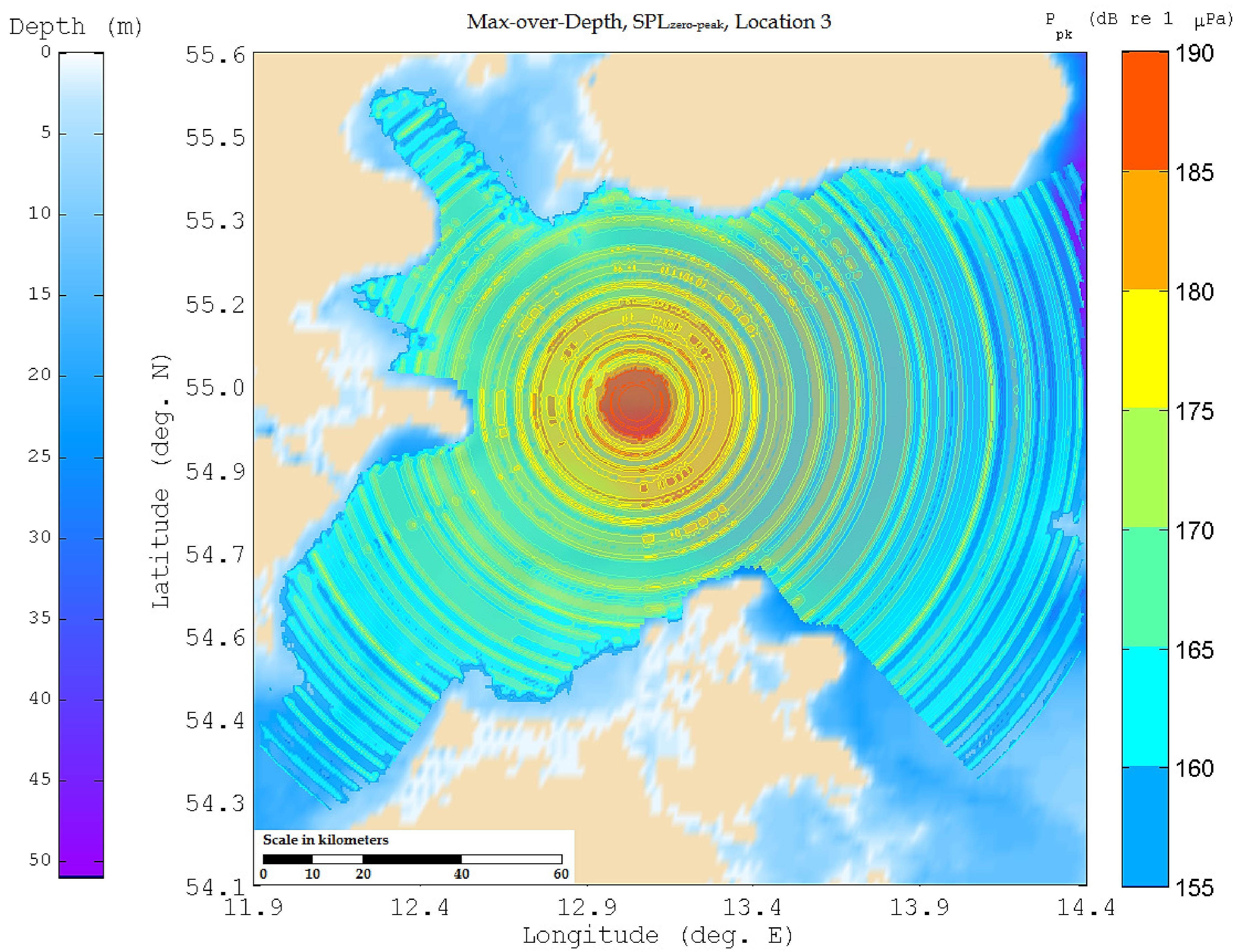


Max-over-Depth, SEL, Location 2
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
SEL_BB (dB re 1 μPa² s)
170
165
160
155
150
145
140
135



Max-over-Depth, SPLzero-peak, Location 2
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
P pk (dB re 1 μPa)
190
185
180
175
170
165
160
155


Max-over-Depth, SEL, Location 3
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
SEL_BB (dB re 1 μPa² s)
170
165
160
155
150
145
140
135



Max-over-Depth, SPLzero-peak, Location 3
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
Ppk (dB re 1 μPa)
190
185
180
175
170
165
160
155

NIRAS

Energinet.dk

APPENDIX 2:
Sound Pressure Level and Sound Exposure Level maps

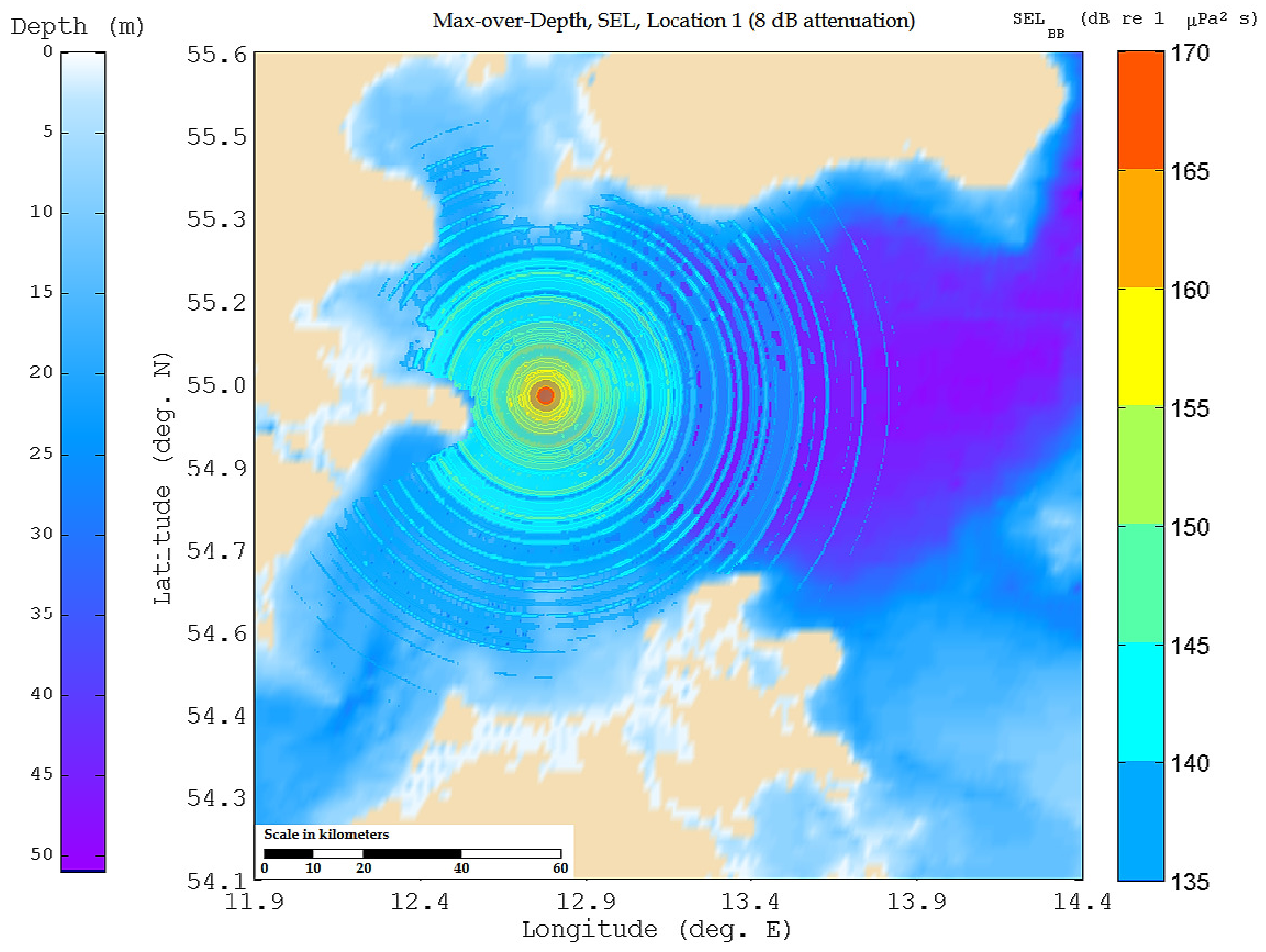
8 dB source level attenuation

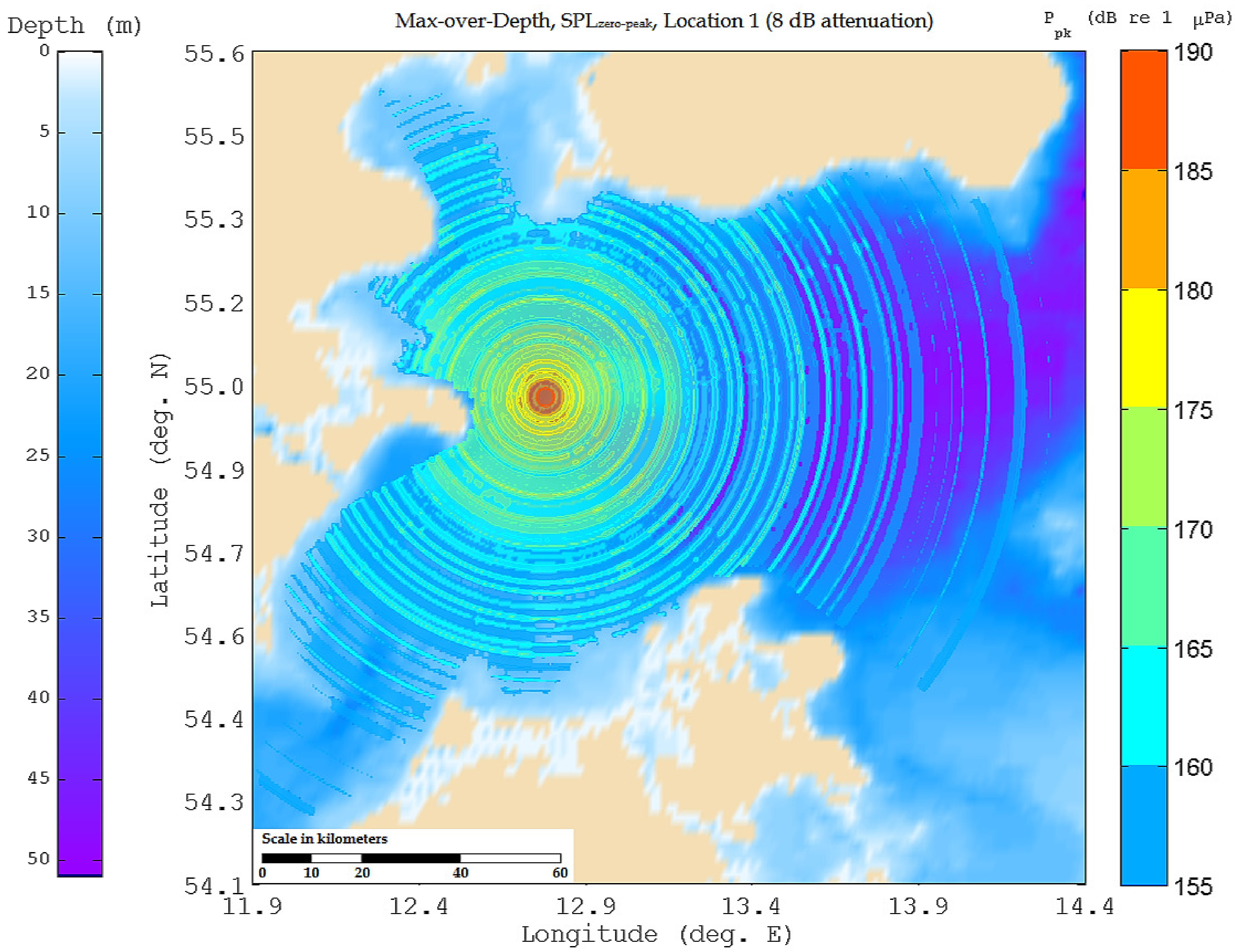
- SEL
- $SPL_{zero\text{-}peak}$

January 2015

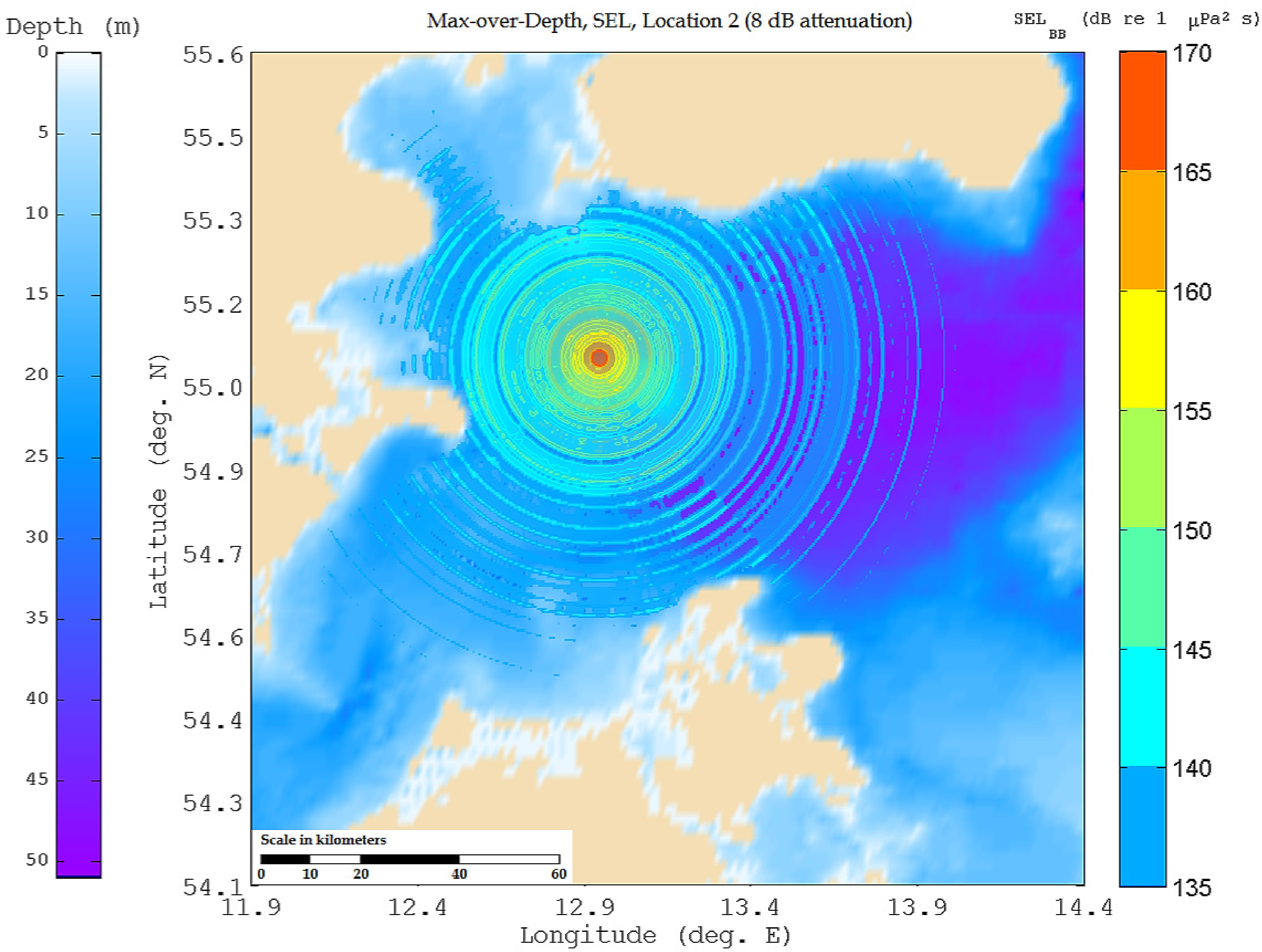
KRIEGERS FLAK OFFSHORE WIND FARM

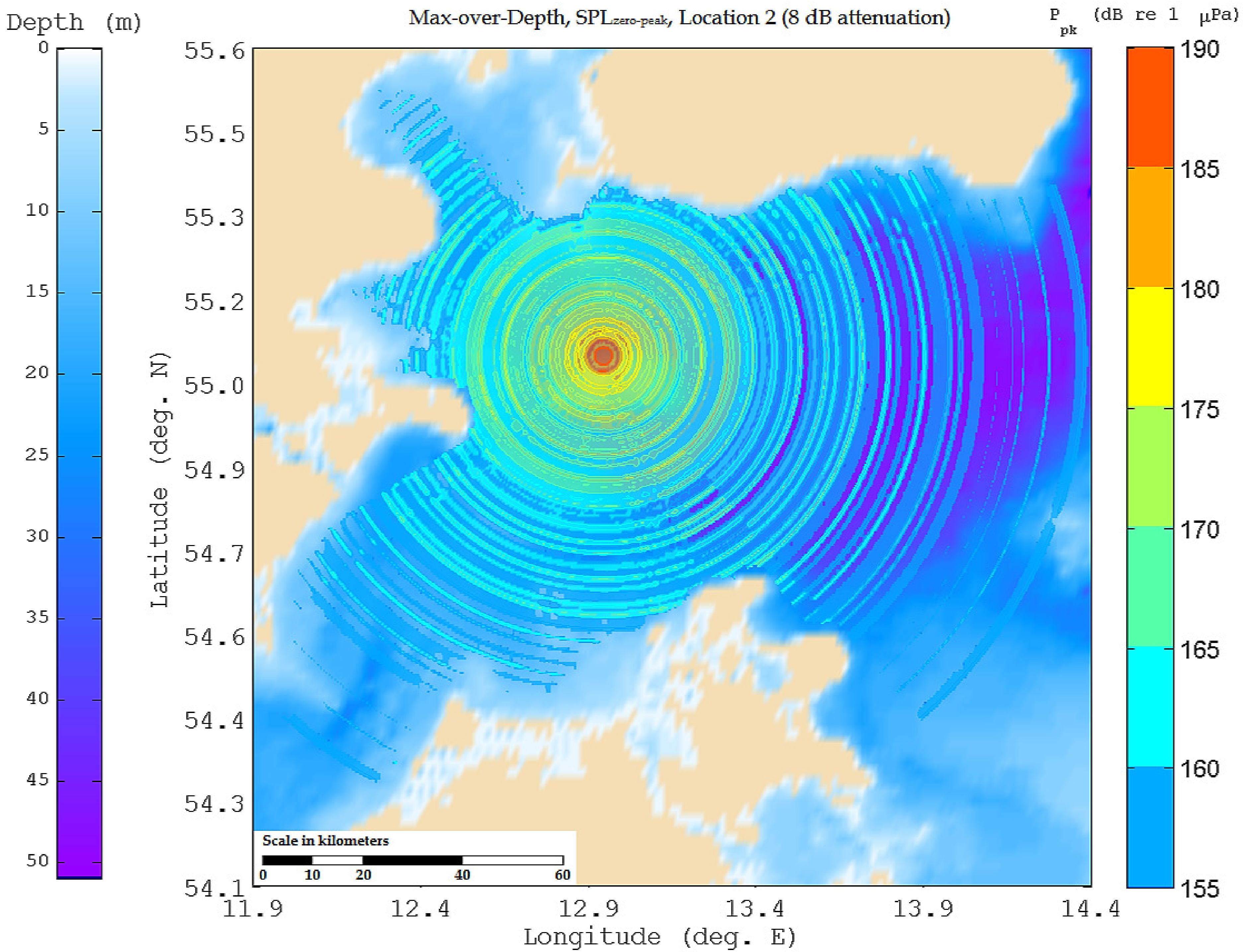
Underwater sound propagation for impact piling operations during construction phase


Max-over-Depth, SEL, Location 1 (8 dB attenuation)
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
SEL_{BB} (dB re 1 μPa² s)
170
165
160
155
150
145
140
135

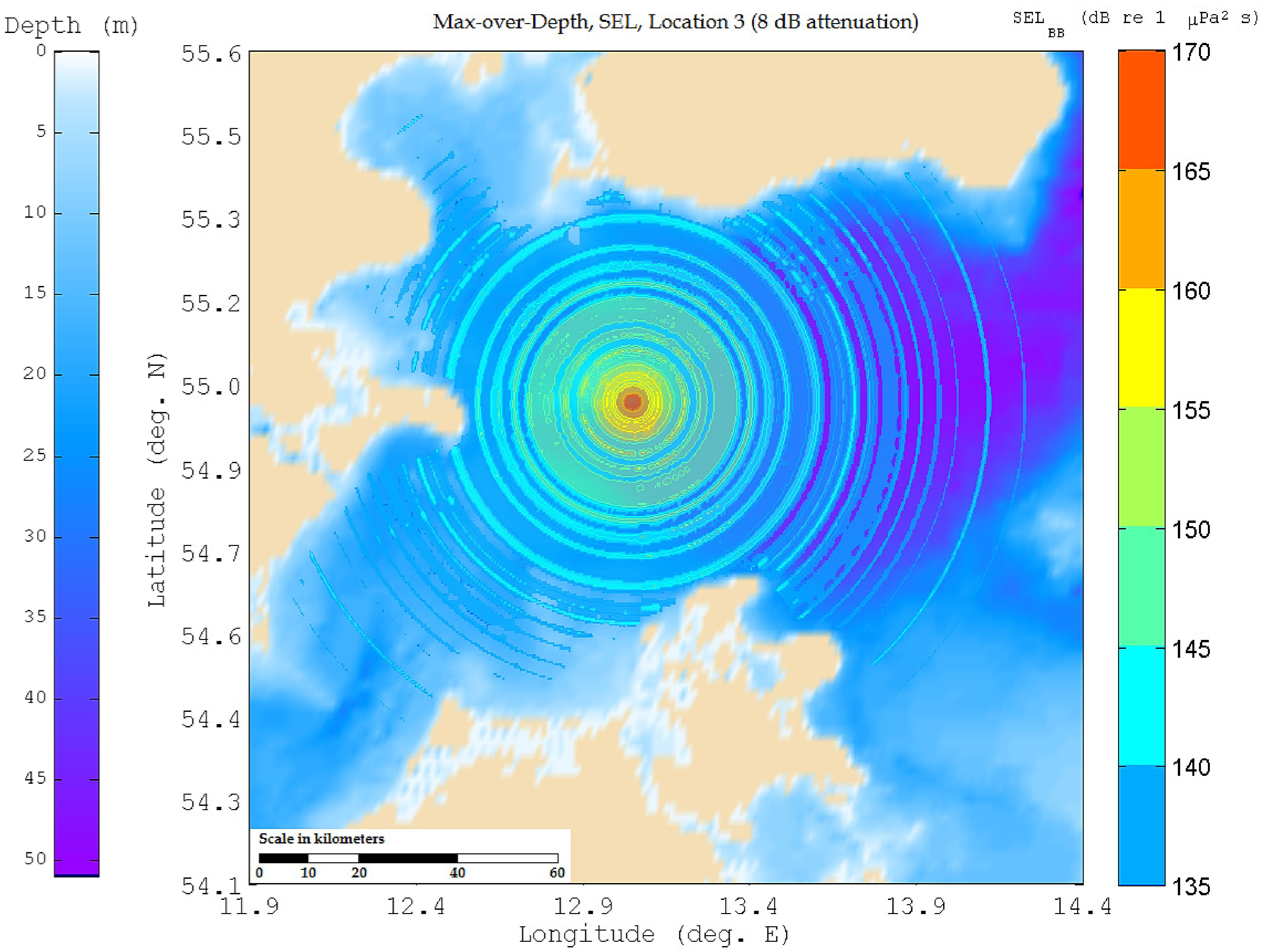


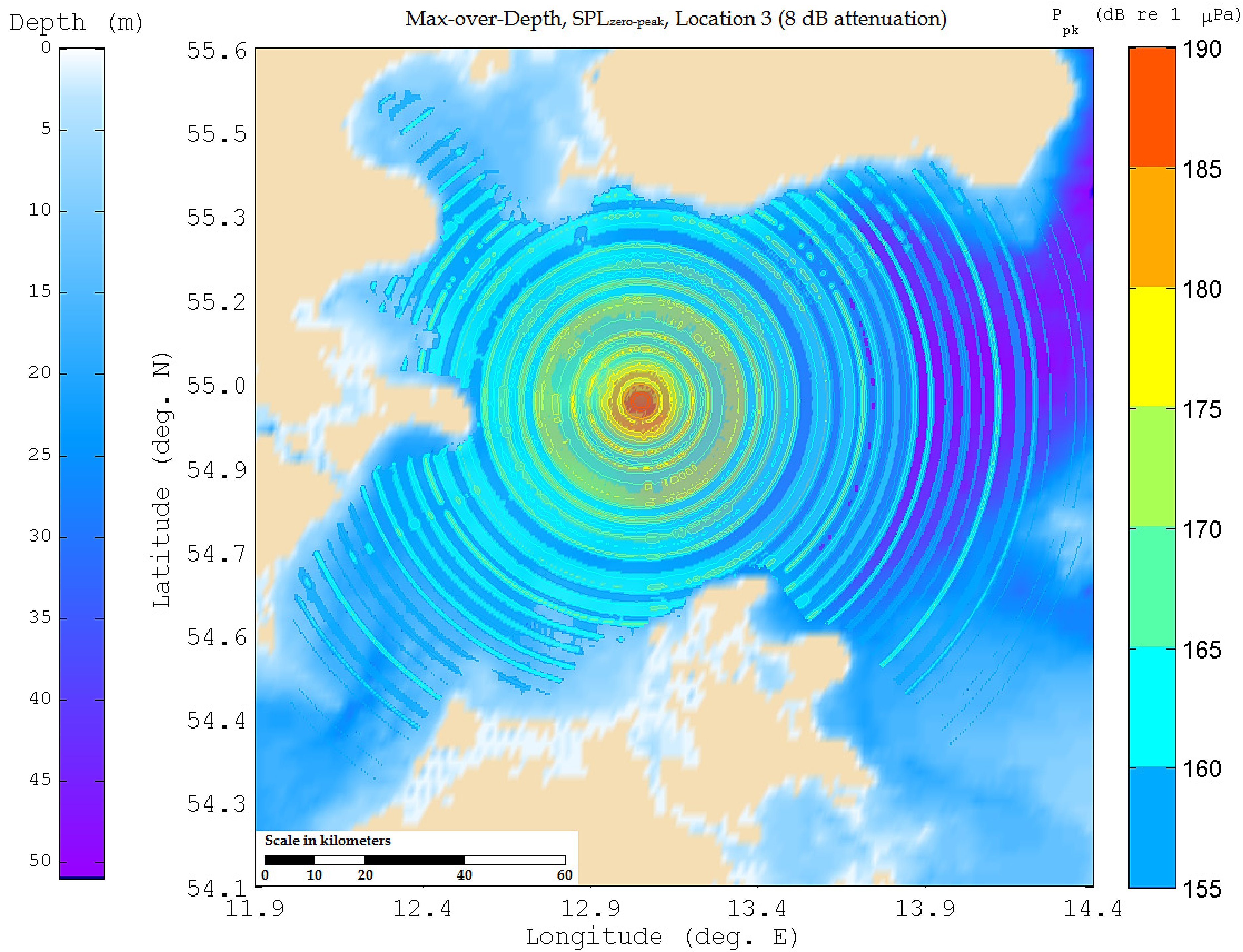
Max-over-Depth, SPLzero-peak, Location 1 (8 dB attenuation)
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
Ppk (dB re 1 μPa)
190
185
180
175
170
165
160
155


Max-over-Depth, SEL, Location 2 (8 dB attenuation)
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
SEL BB (dB re 1 μPa² s)
170
165
160
155
150
145
140
135



Max-over-Depth, SPLzero-peak, Location 2 (8 dB attenuation)
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
Ppk (dB re 1 μPa)
190
185
180
175
170
165
160
155


Max-over-Depth, SEL, Location 3 (8 dB attenuation)
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
SEL BB (dB re 1 μPa² s)
170
165
160
155
150
145
140
135


Max-over-Depth, SPLzero-peak, Location 3 (8 dB attenuation)
Depth (m)
0
5
10
15
20
25
30
35
40
45
50
Latitude (deg. N)
55.6
55.5
55.3
55.2
55.0
54.9
54.7
54.6
54.4
54.3
54.1
Longitude (deg. E)
11.9
12.4
12.9
13.4
13.9
14.4
Scale in kilometers
0
10
20
40
60
Ppk (dB re 1 µPa)
190
185
180
175
170
165
160
155