Modelling Cumulative Sound Exposure Along a Seismic Line to Assess the Risk of Seismic Research Surveys on Marine Mammals in the Antarctic Treaty Area

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1 Introduction

Numerical modelling of sound propagation is an essential tool to assess the potential risk of air-gun shots on marine mammals and derive exposure zone radii within which certain hearing thresholds are exceeded. Here, the results of a detailed 2.5D finite-difference (FD) modelling study are presented, which takes *(i)* the sound velocity profile of the water column, *(ii)* interactions with the seafloor and *(iii)* cumulative effects from multiple shots fired along a seismic line into account, approximates the compact air-gun clusters deployed by R/V *Polarstern* in polar regions by 'point source equivalents' and simulates marine mammals as static receivers *(Breitzke and Bohlen 2010)*. It is a contribution to a strategic risk assessment study on the impact of seismic research surveys on marine mammals in the Antarctic Treaty Area *(Boebel et al. 2009)*.

2 Study Area & Model Parameters

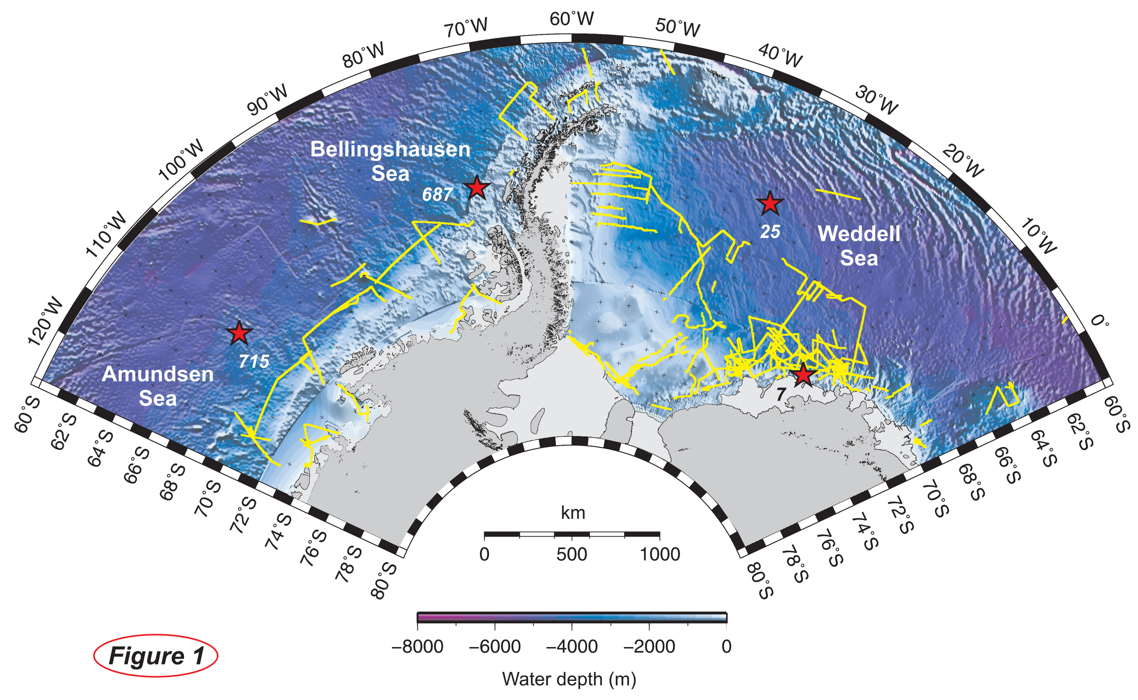

Figure 1

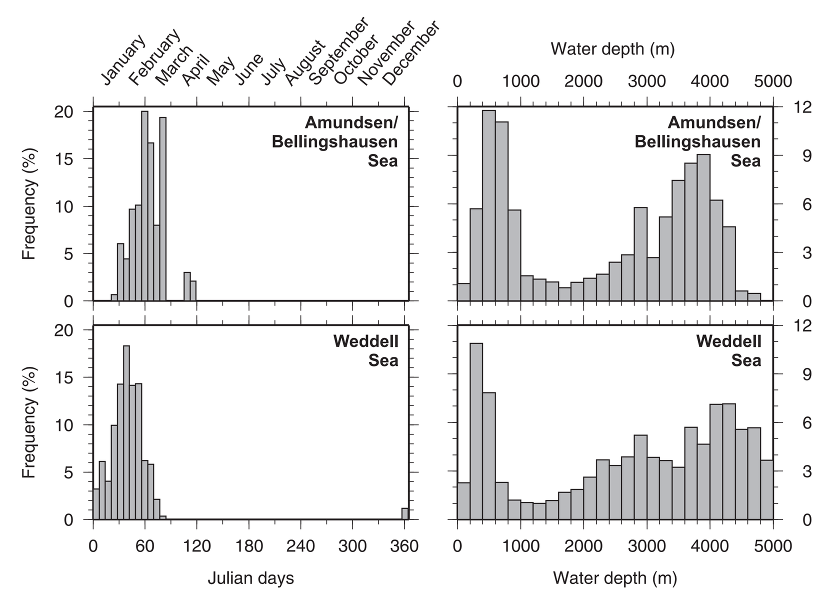

Figure 2

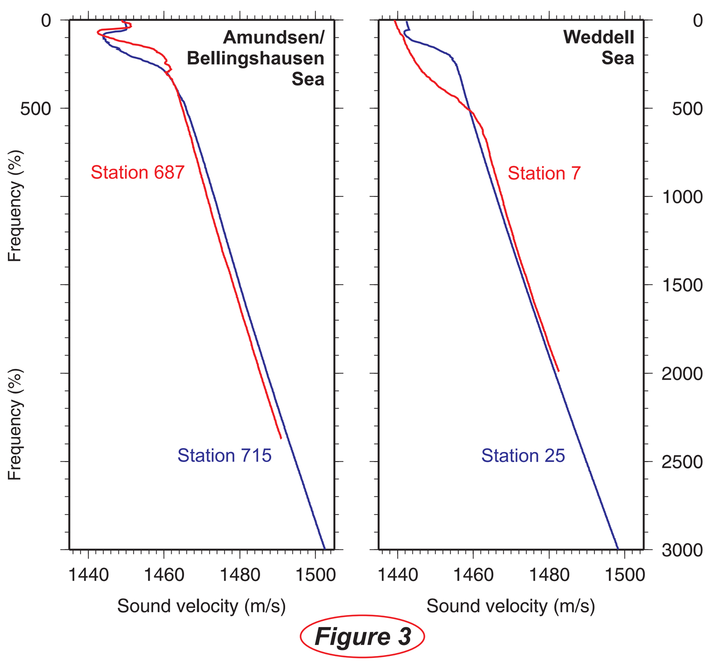

Figure 3

The modelling study focuses on the Amundsen/Bellingshausen and the Weddell Seas, where most of the multichannel seismic (MCS) research activities were conducted with R/V *Polarstern* since it was taken in service in 1982 (**Fig. 1**). Most of these MCS lines were collected during the austral summer months and covered water depths between ~200 - 1000 m and ~3000 - 4500 m (**Fig. 2**). Typical sound velocity profiles show a ~150 - 250 m thick cold low-velocity sound channel close to the sea surface, overlain by a thin (~10 - 30 m) layer of warmer water masses with higher sound velocity, and underlain by a positive sound velocity gradient (**Fig. 3**). From these data the following typical models are derived:

Deep water models:	3000 m water depth	Seafloor reflection coefficient:	R = 0.2	Ship speed:	5 kn
Shallow water models:	400 m water depth	Seismic profile length:	L = 10 km	Shot interval:	10 s - 60 s

3 Modelling Approach

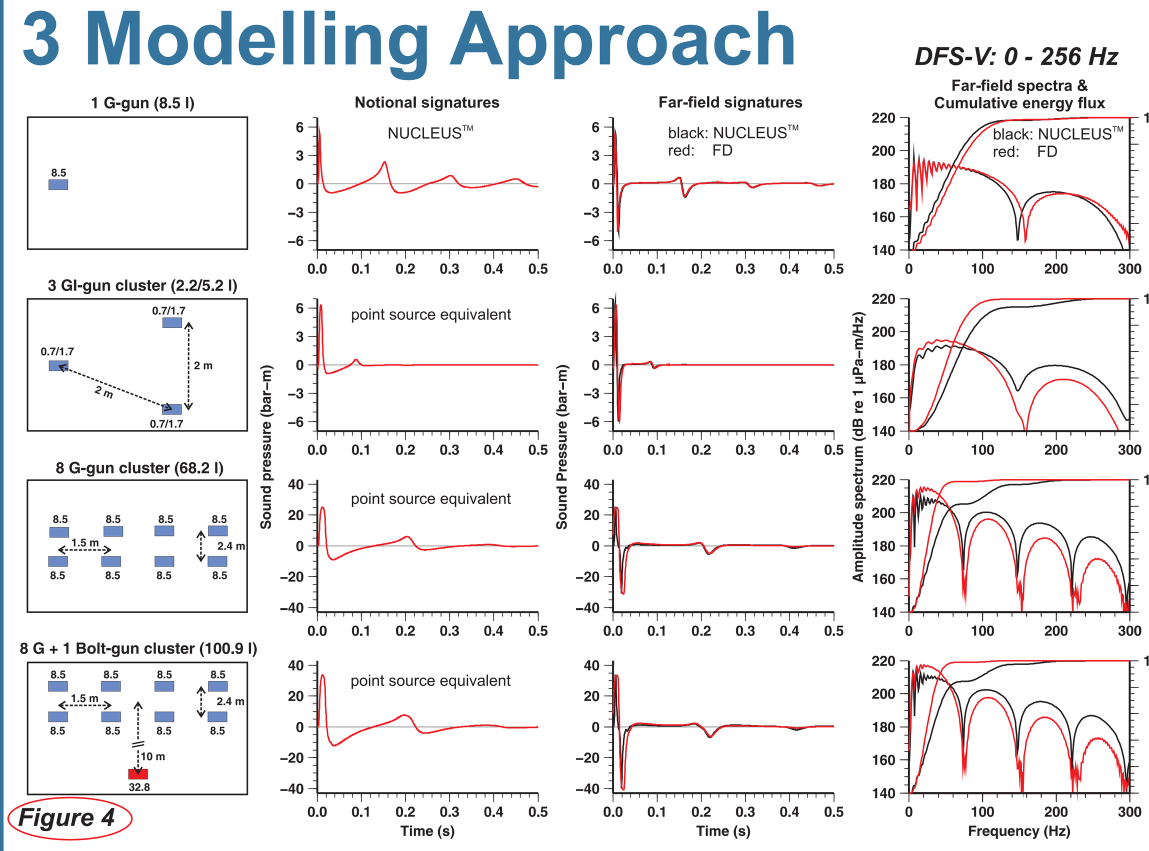

Figure 4

The modelling approach consists of 3 steps: Modelling (a) the seismic source, (b) sound propagation due to a single shot, (c) cumulative SELs due to multiple shots fired along a seismic line and exposure histories received by static marine mammals.

3a Seismic Source

Source signatures are computed by the NUCLEUS™ source modelling package (**Fig. 4**). 4 air-gun configurations are considered: A single G gun (8.5 l), 3 GI-gun cluster (2.2 l/5.2 l), an 8 G-gun cluster (68.2 l), an 8 G-gun cluster + 1 Bolt 1500 LL (100.9 l). The configurations are approximated by 'point source equivalents'. That is, in case of the single G gun the notional signature *n(t)* is used as source signal, in case of the compact air-gun clusters the time-integrated far-field signature *f(t)* is used as source signal $\tilde{n}(t) = \int f(t)dt$.

3b Sound Propagation (single shot)

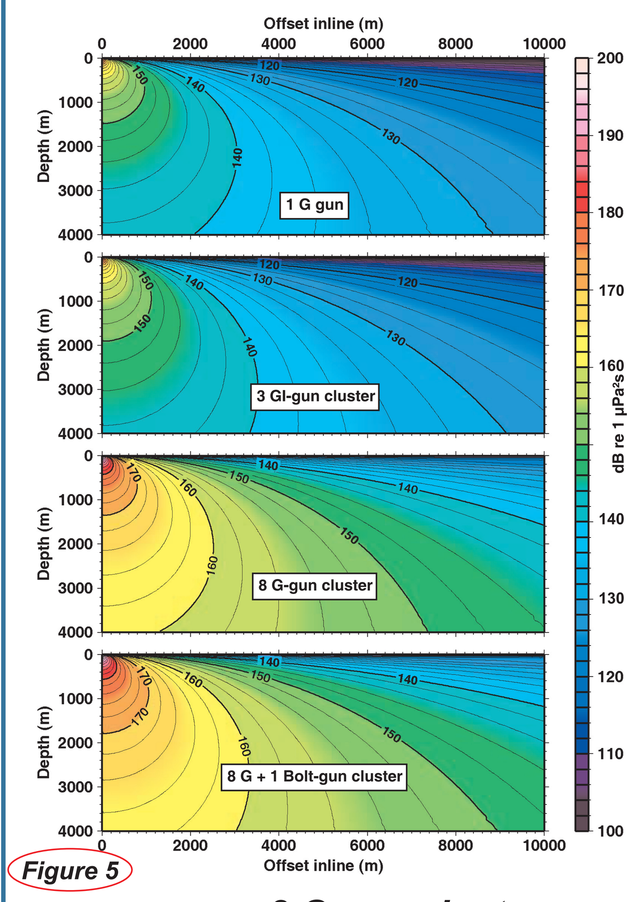

Figure 5

A 2.5D FD code, which implies cylindrical symmetry, is used for modelling sound propagation due to a single shot *(Bohlen 2002)*. From a grid of synthetic seismograms, distributed equidistantly over the model, a 2D SEL field of a single shot, displayed for a semi-infinite iso-velocity model and the 4 air-gun configurations (**Fig. 5**), are derived. They show the typical dipole-like directivity of single shots.

3c₁ Cumulative SELs

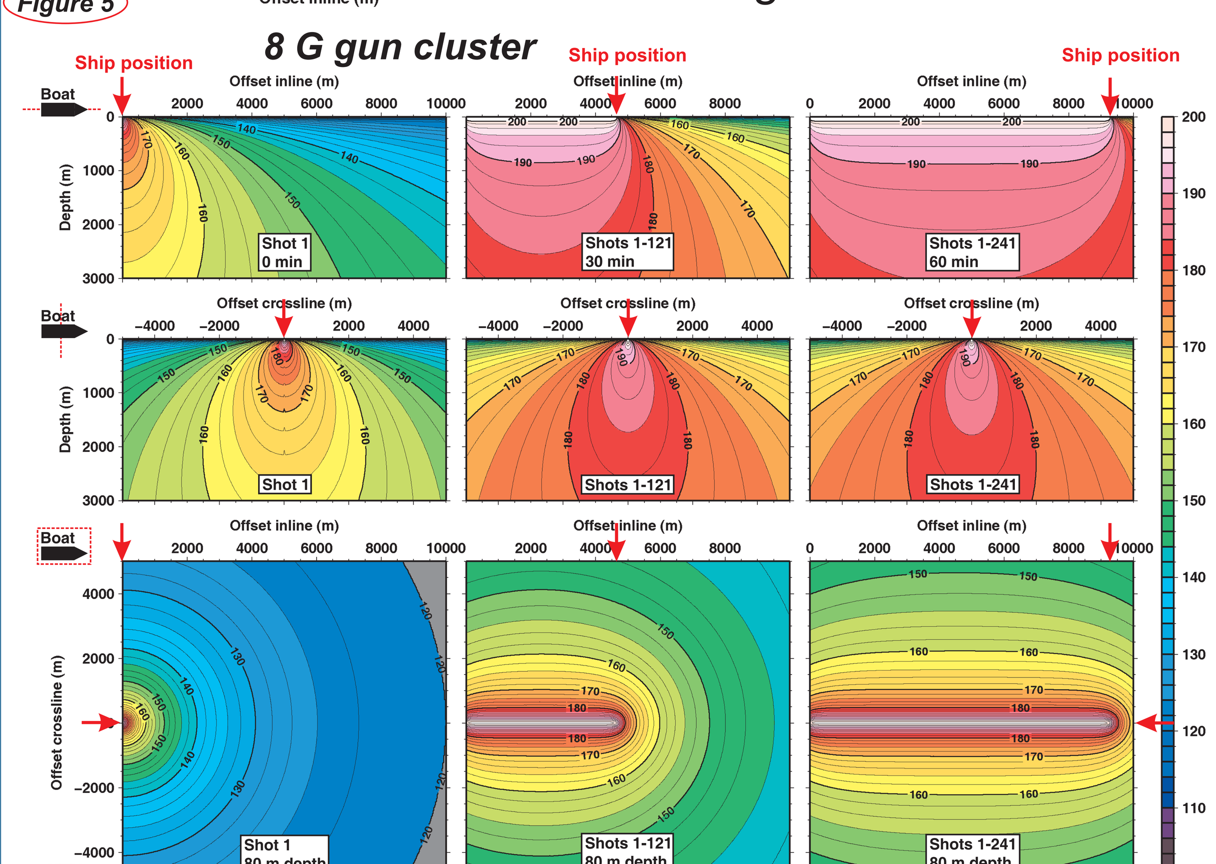

Figure 6

The cumulative impact of multiple shots is determined by superposing the 3D SEL fields of the single shots moving along the seismic line according to the ship speed and shot interval. The resulting 3D cumulative SEL field, displayed in 3 perpendicular planes for a semi-infinite iso-velocity model (**Fig. 6**), shows a tubular-like structure along the seismic line with maximum levels beneath the line.

3c₂ Exposure Histories

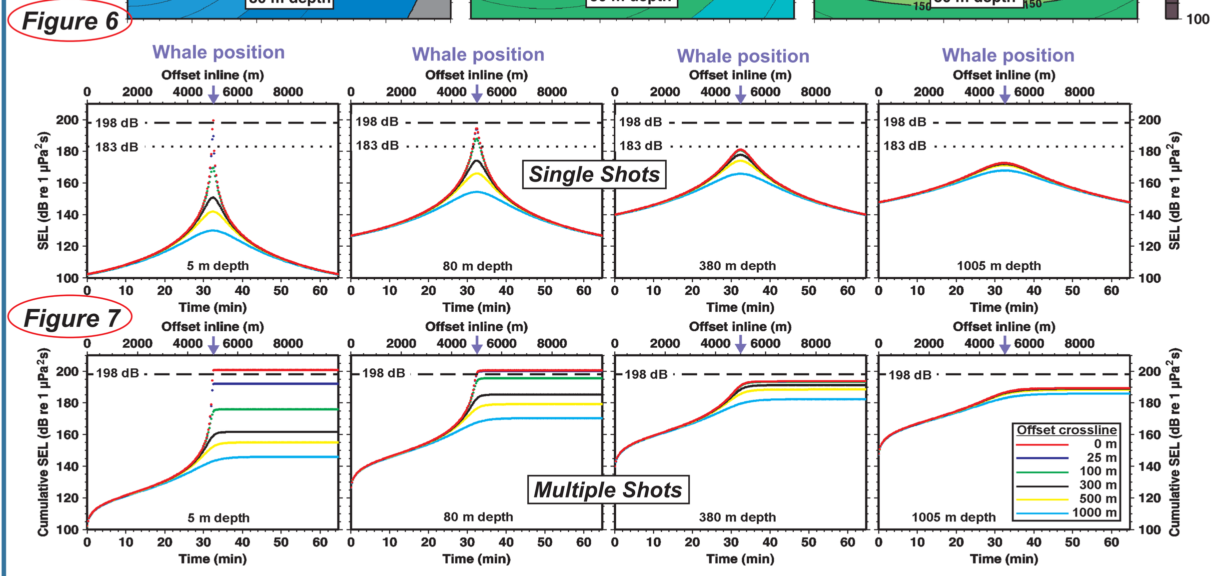

Figure 7

Time-dependent exposure histories received by static marine mammals can also be extracted (**Fig. 7**). They reach a plateau, if the ship has passed the animal's position. Close to the sea surface, they strongly depend on the animal's offset crossline.

4 Application to the Southern Ocean

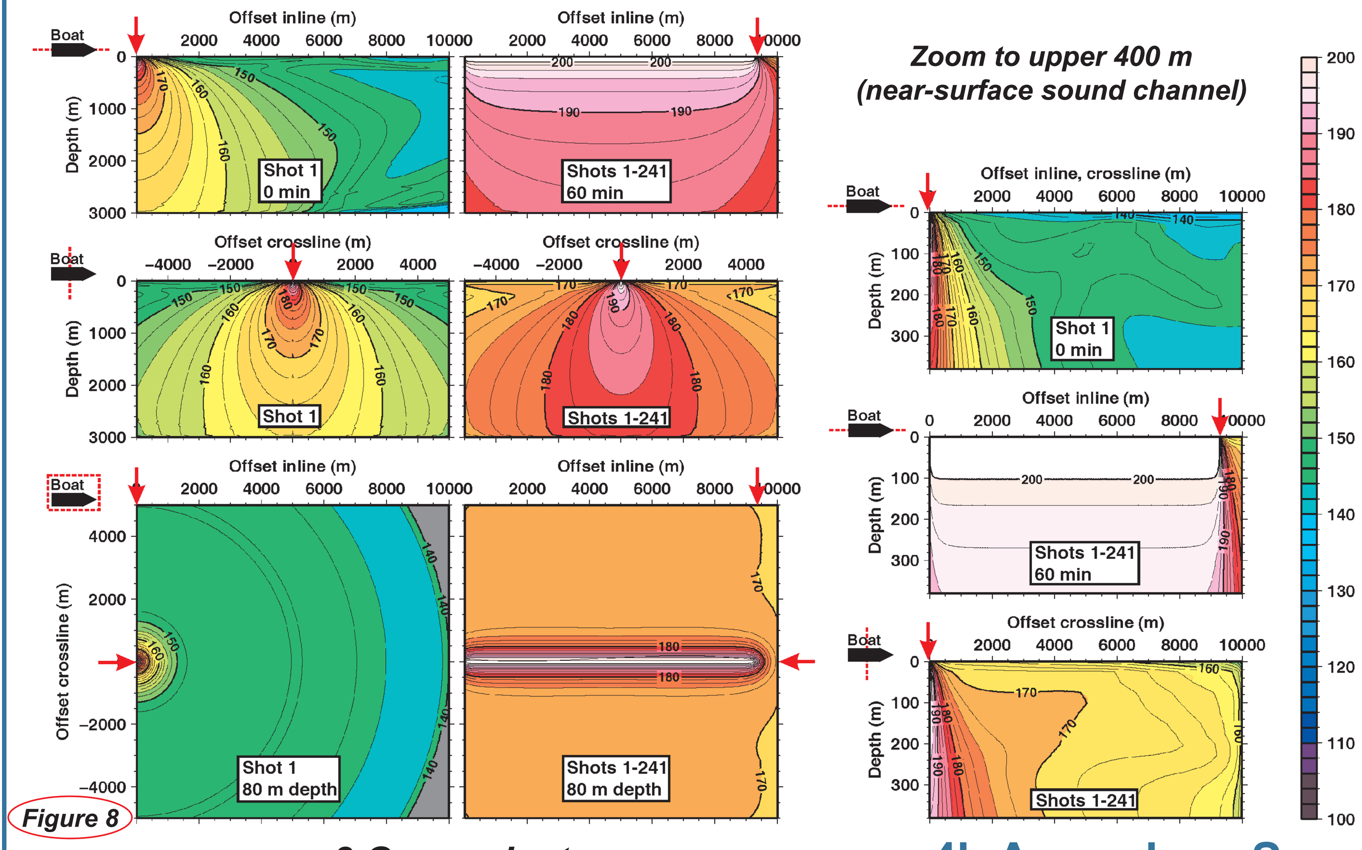

Figure 8

4a Amundsen Sea - Deep Water 715

Application to the Southern Ocean shows, that the near-surface sound channel and the sound velocity gradient cause distortions of the SEL contour lines, especially in deep waters. But only low to moderate levels are affected (**Fig. 8**).

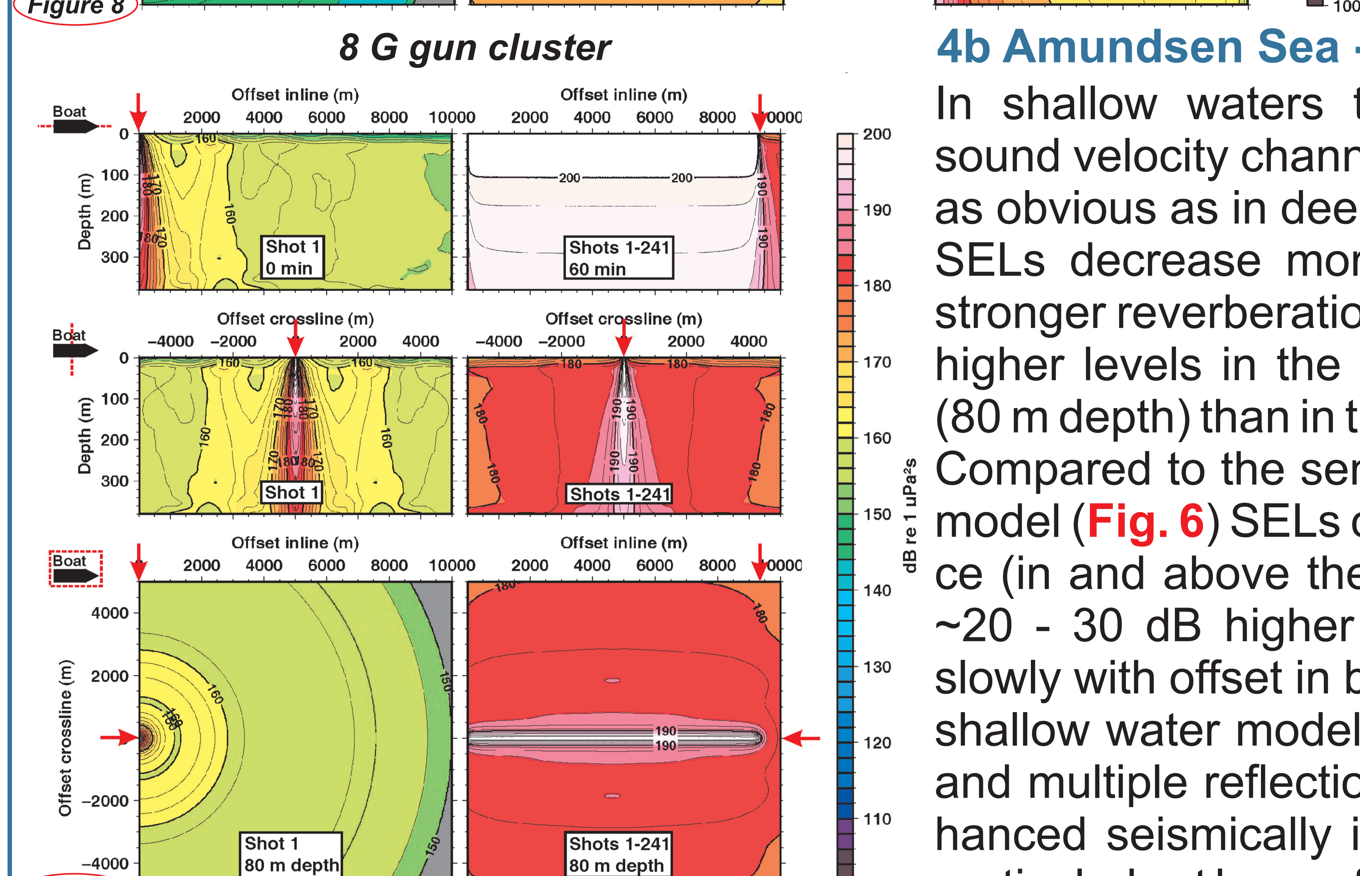

Figure 9

4b Amundsen Sea - Shallow Water 687

In shallow waters the influence of the sound velocity channel and gradient is not as obvious as in deep waters (**Fig. 9**). But SELs decrease more slowly due to the stronger reverberations, leading to ~10 dB higher levels in the shallow water model (80 m depth) than in the deep water model. Compared to the semi-infinite iso-velocity model (**Fig. 6**) SELs close to the sea surface (in and above the sound channel) are ~20 - 30 dB higher and decrease more slowly with offset in both the deep and the shallow water models due to the seafloor and multiple reflections. This leads to enhanced seismically induced noise levels, particularly at large offsets (**Fig. 10**).

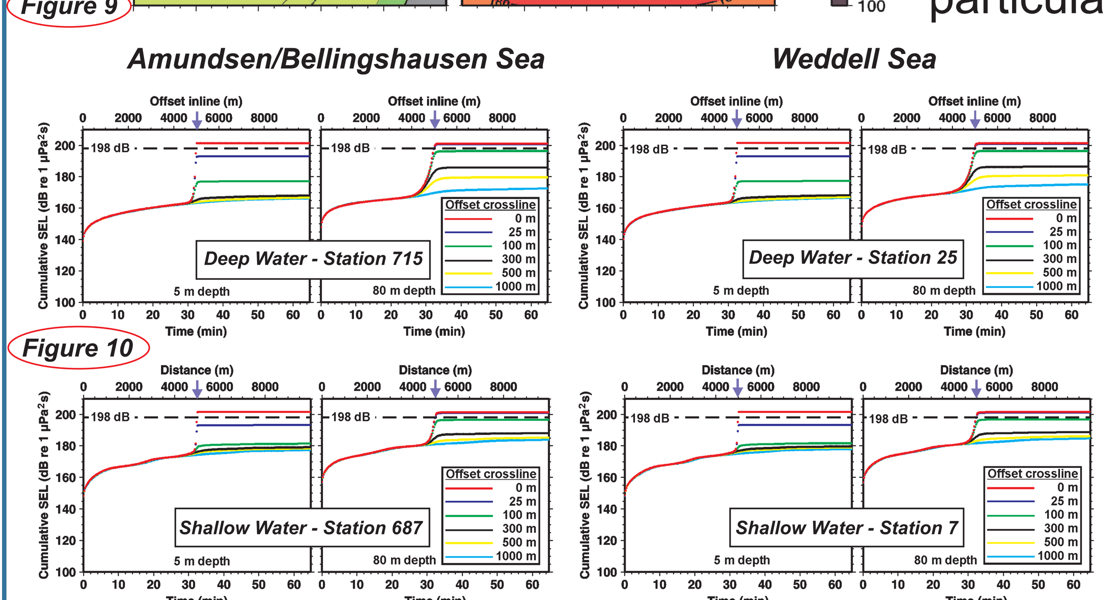

Figure 10

4c Exposure Histories

Exposure histories received by marine mammals above (5 m) and in the sound channel (80 m) do not show pronounced differences between both deep and both shallow water models (**Fig. 10**). This indicates, that the fine-scale sound velocity structure of the Southern Ocean does not affect the sound propagation of seismic frequencies significantly.

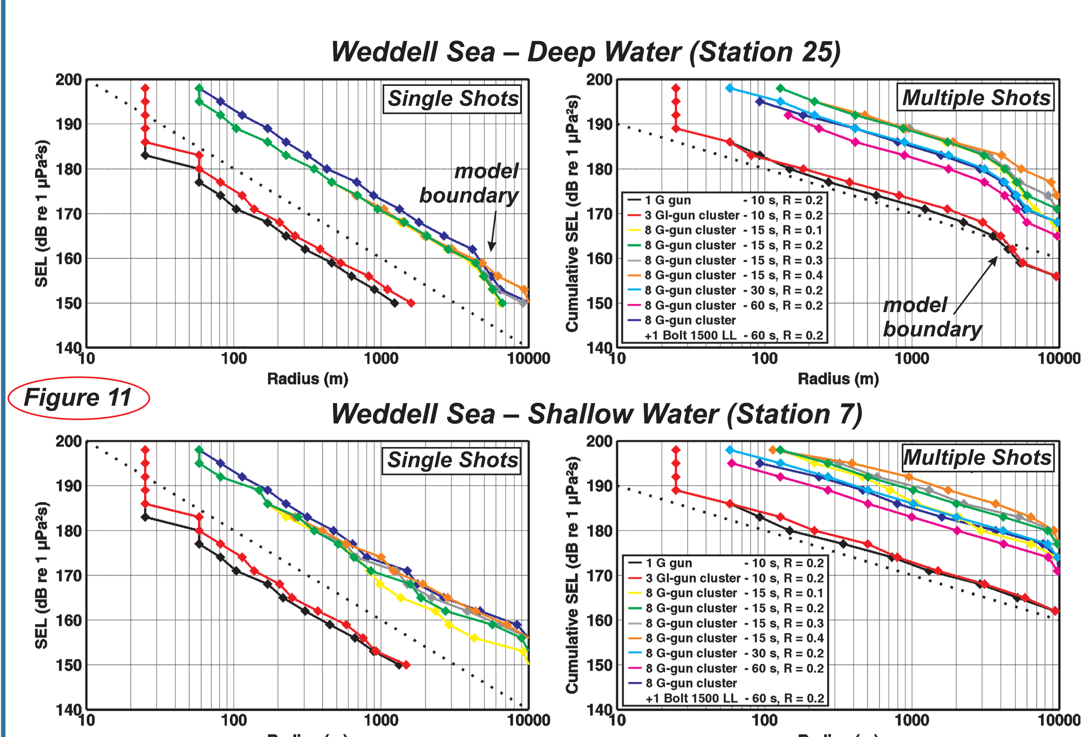

Figure 11

4d Exposure Zone Radii

Exposure zone radii derived for different thresholds depend on the air-gun configuration, but are almost independent of the environmental parameters (**Fig. 11**). In case of single shots radii can be predicted from the source level using a spherical spreading law. In case of multiple shots radii follow a cylindrical spreading law, and the source SEL and shot interval determine the intercept.

References

Boebel O, Breitzke M, Burkhardt E, Bornemann H (2009) Strategic Assessment of the risk posed on marine mammals by use of air guns in the Antarctic Treaty Area. Information Paper IP51, Agenda Item: CEP 8c, Antarctic Treaty Consultative Meeting XXXII, Baltimore, USA, 273 pp.
Bohlen T (2002) Parallel 3-D viscoelastic finite difference modelling. Comp. Geosci. 28: 887-899.
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