KEYNOTE FOR JOMOPANS MIDTERM EVENT, ROYAL SOCIETY, LONDON

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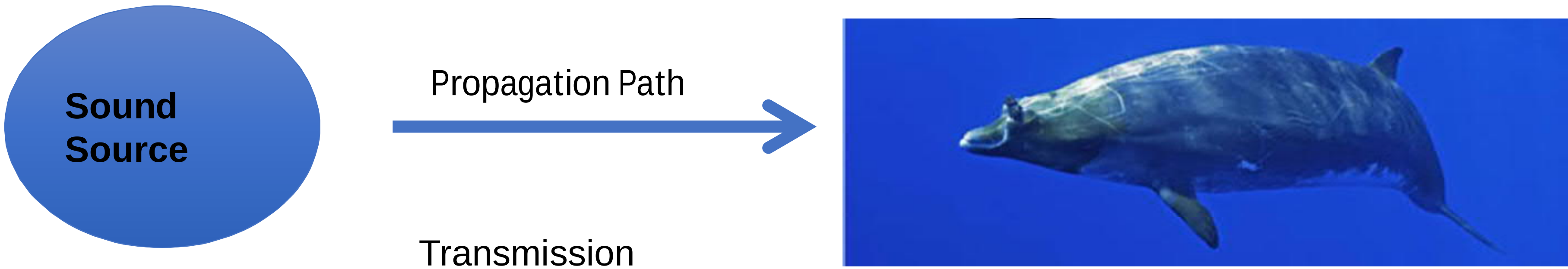
Overall Summary

- Why is sound important to marine animals and how do they use it?
- What are the effects of ocean noise on marine life?
- Evidence on appropriate dosage measures for specific effects should drive decisions about how to measure ocean noise to estimate effects
- What are the highest priority basic scientific problems required to improve estimates of effects?
- How does this relate to JOMOPANS?

Outline for First Part of the Talk …

- Understanding underwater sound
  - Source – Propagation – Reception Model
  - Decibel
- Why is sound important to marine animals?
  - Best distance sense underwater
  - Echolocation can replace vision
- How does sound affect marine life?
  - Zones of influence
  - Farthest - Masking
  - Closest - Injury

Source-Propagation-Receiver Model



Source Level:
Loudness
Referred to 1 m range
from source

Transmission
Loss: Loss of Sound
Energy as it propagates
from source

Receiver

The Decibel Scale

The decibel is a logarithmic scale:

If p is a pressure, then

Sound Pressure Level (dB) = 20 $\log_{10}(p/p_{ref})$

$P_{ref} = 1\ \mu Pa$

$100/1 = 10^2 = 40$ dB

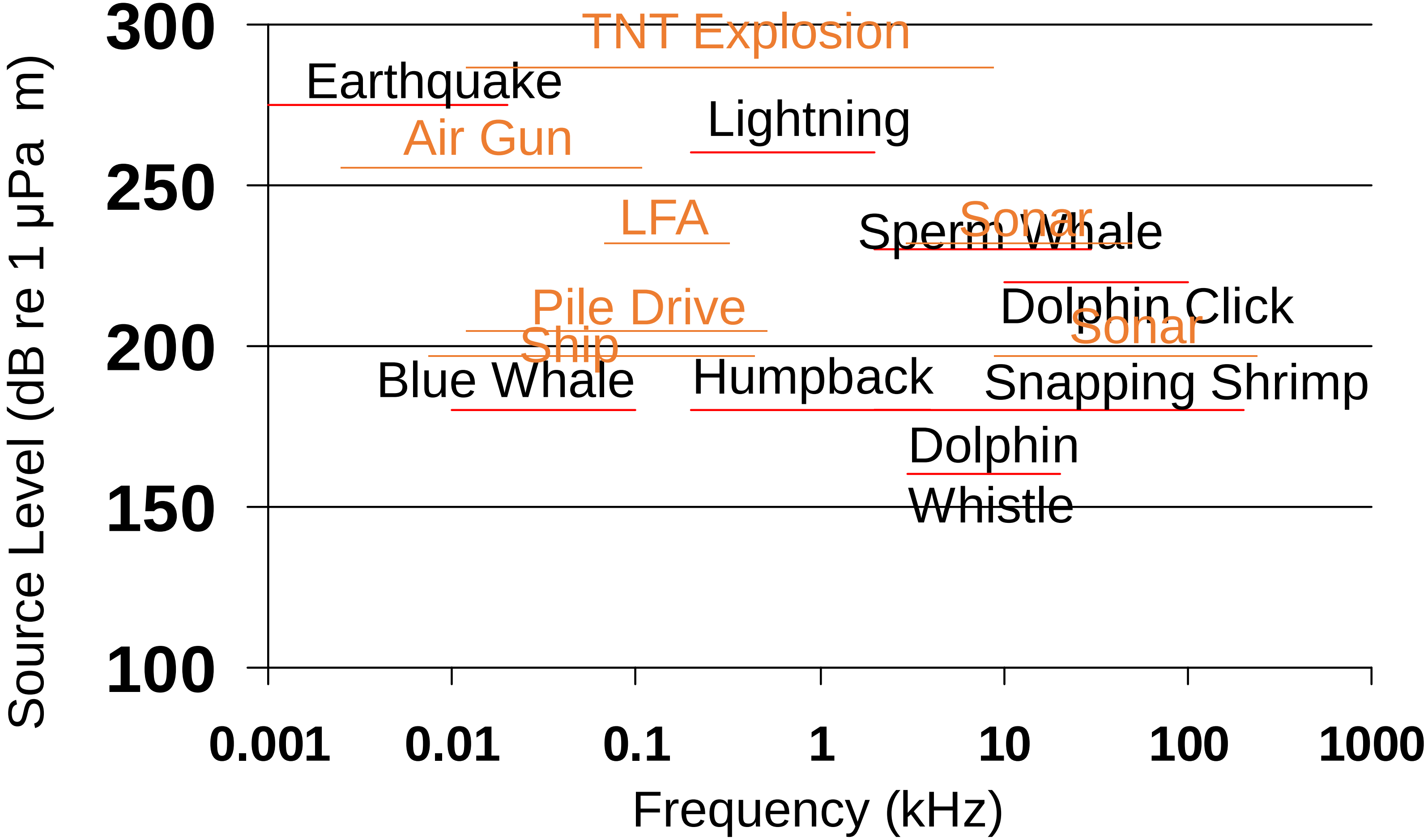
$10^6 = 120$ dB

$1/100 = 10^{-2} = -40$ dB

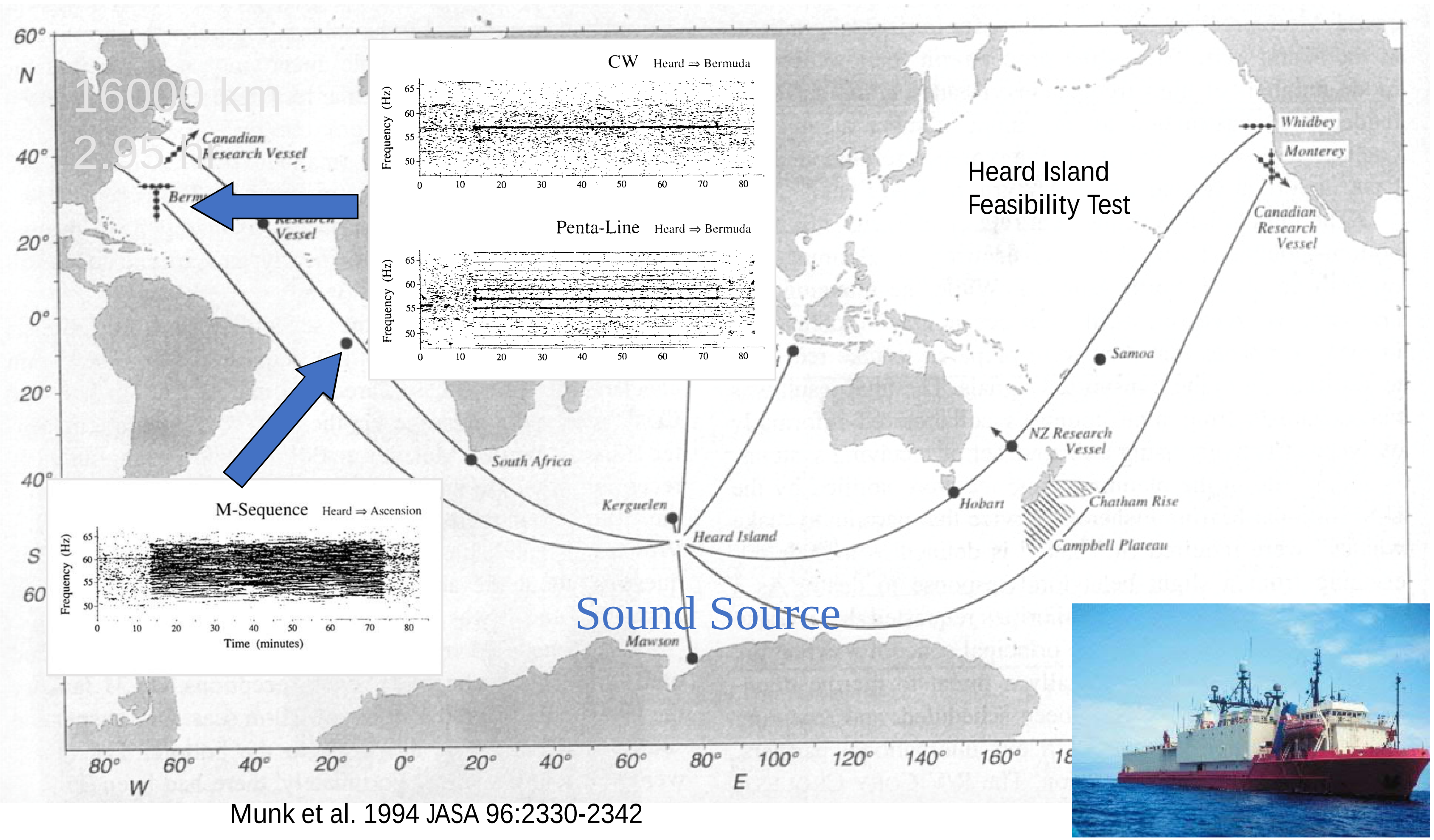
Remember

$x = \log_{10}(10^x)$

Over the past century, humans started producing sound in the ocean that may interfere with marine mammal use of sound



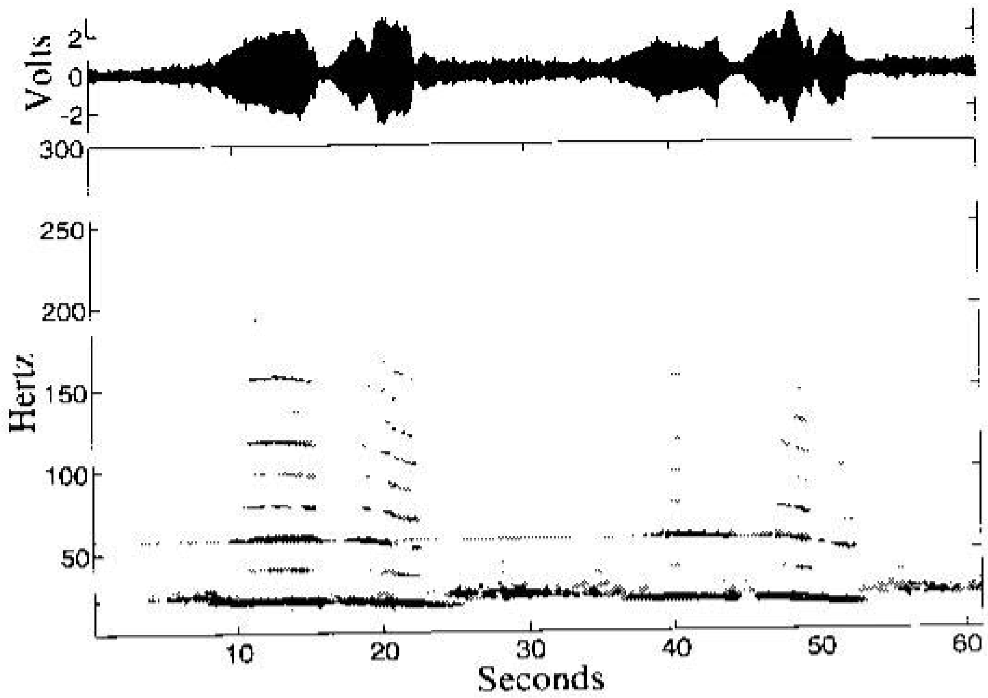
Low frequency sound propagates great distance in the ocean



Munk et al. 1994 JASA 96:2330-2342

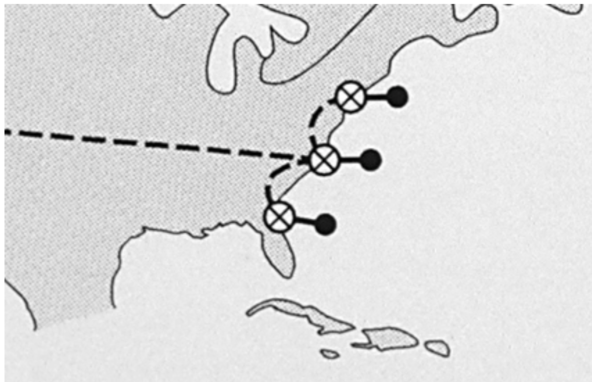
Low frequency calls of blue whales

- Duration 10-20 sec
- Frequency 8-15 Hz strong harmonics
- Varies with geographical region
- Produced by males during breeding season

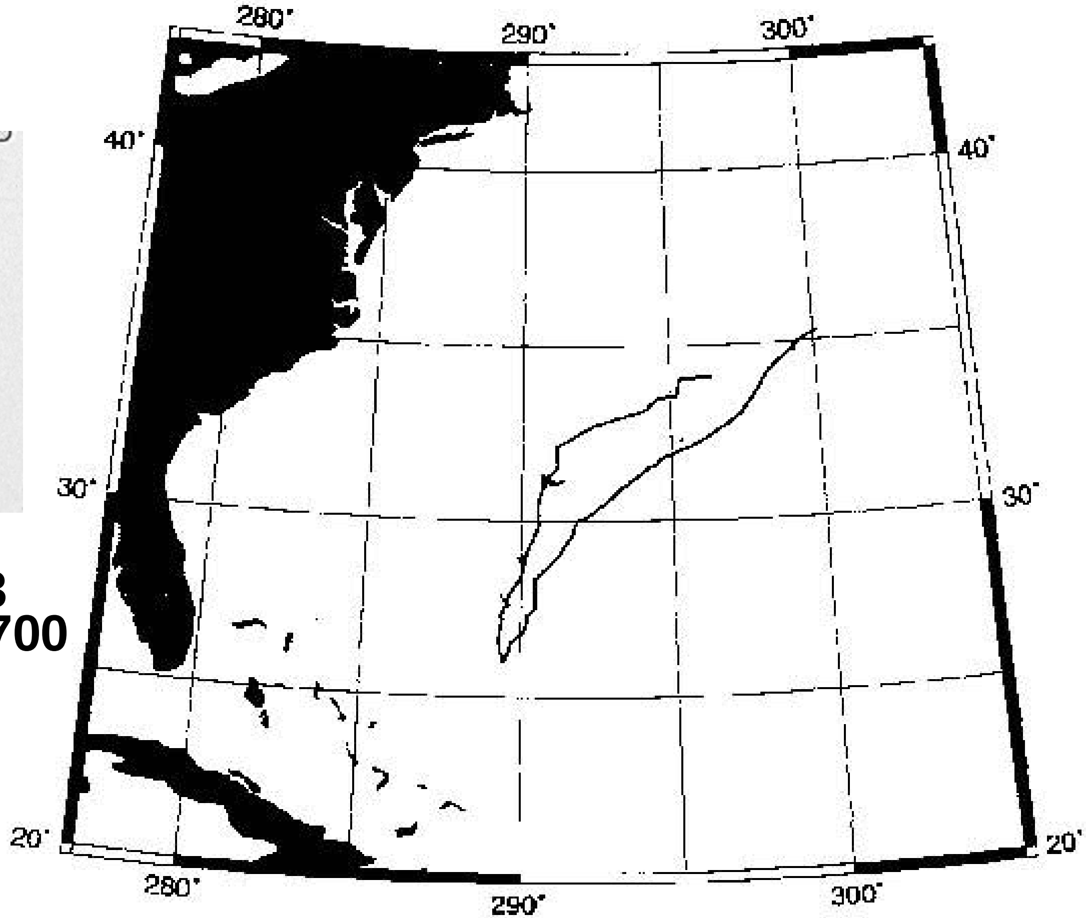


Long range detection of blue whale call

Tracked by US Navy SOSUS array

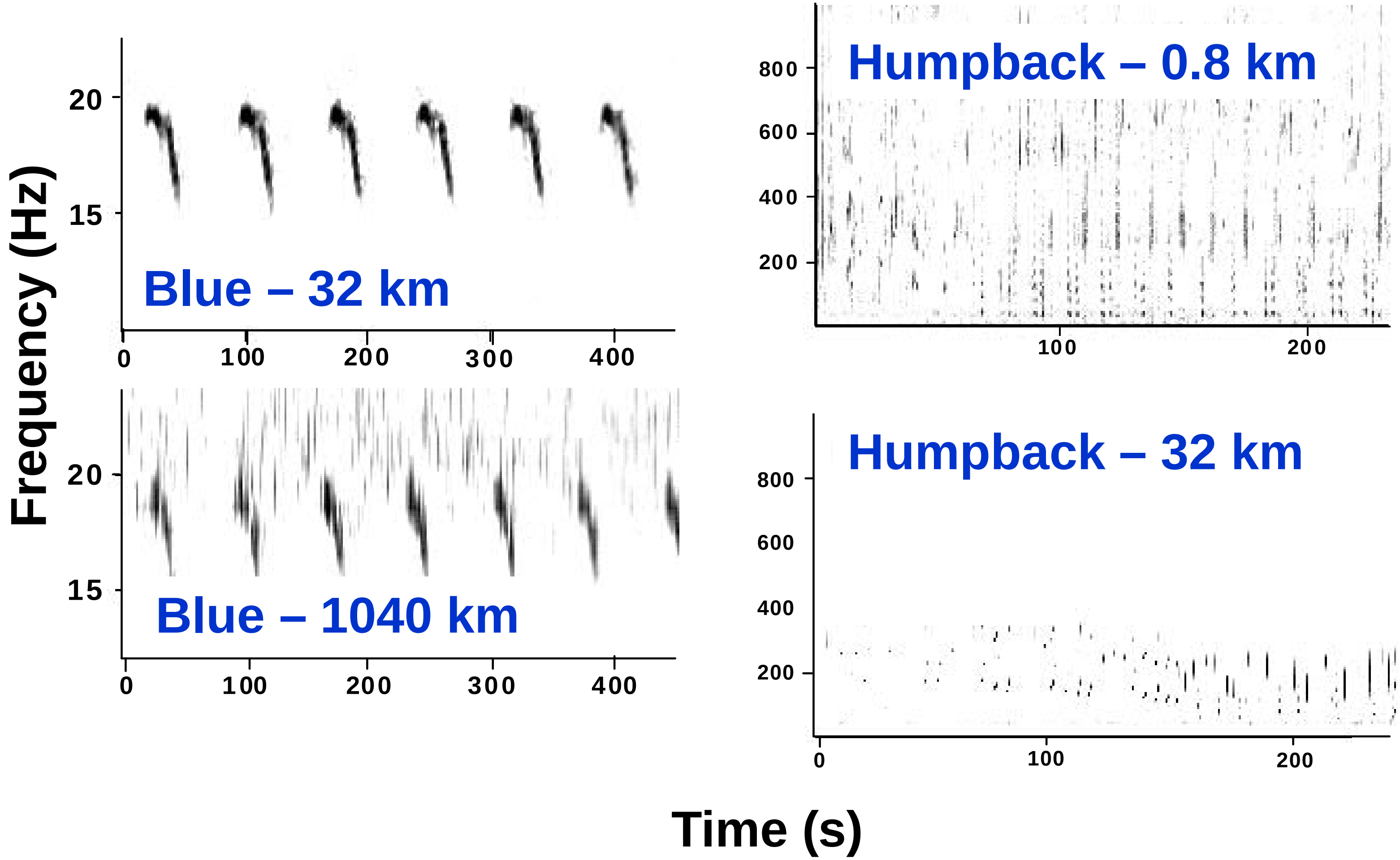


- **Whale tracked for 43 days as it swam > 1700 km**



Courtesy Christopher Clark, Cornell University

Low Frequency Sound Propagates Further

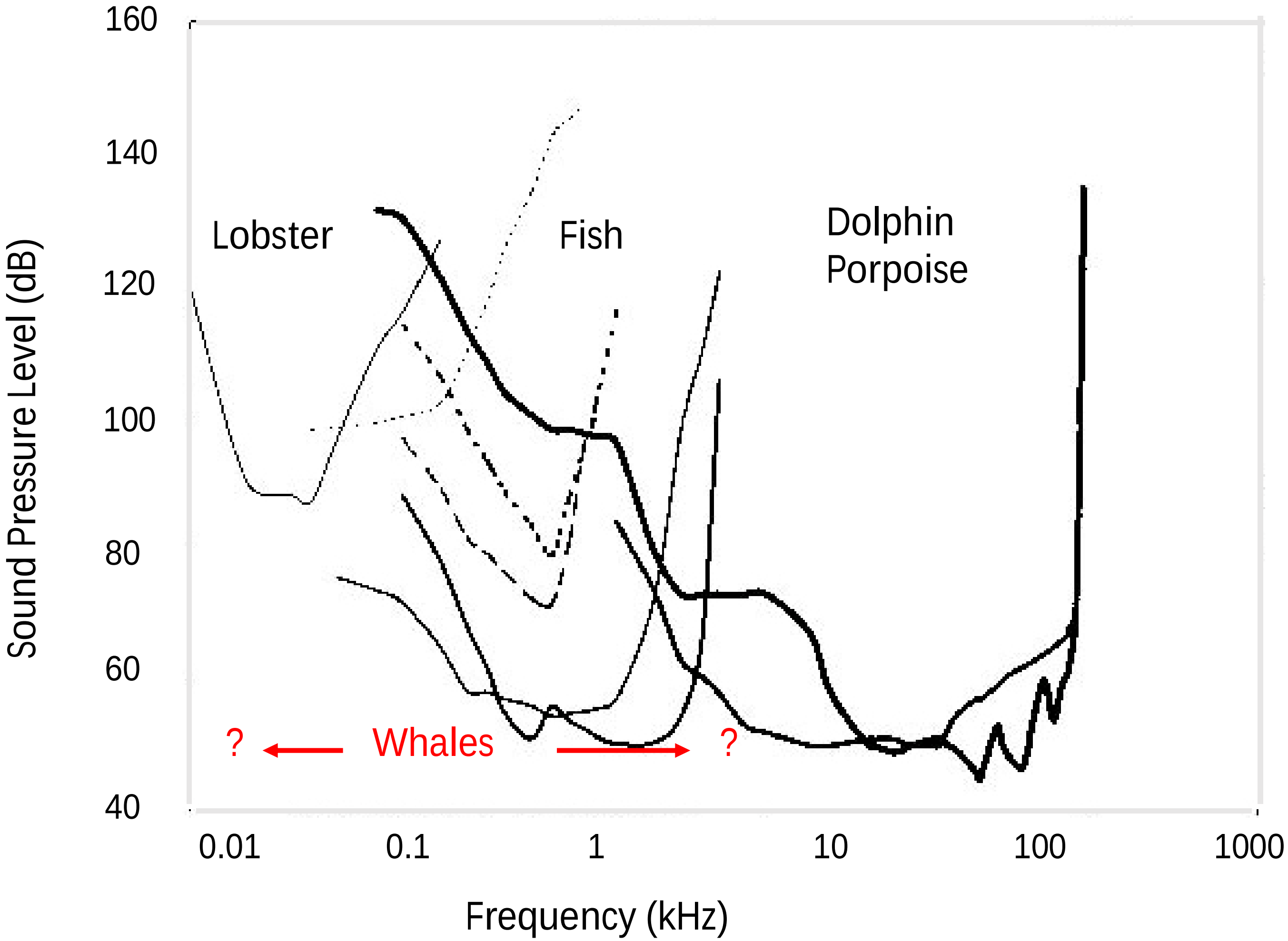


Courtesy C. Clark, Cornell

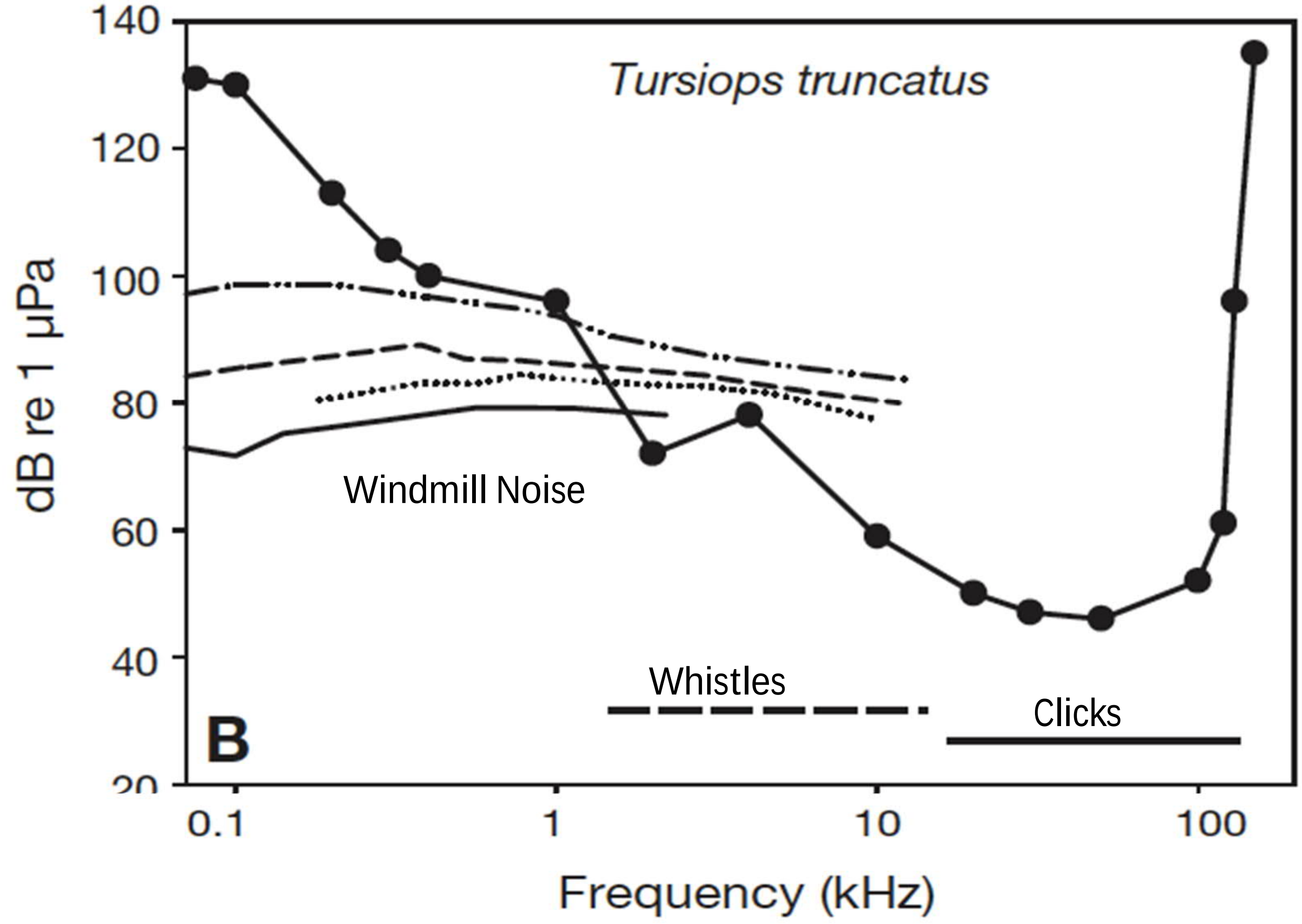
Limits to detecting a signal

- Hearing: a sound cannot be detected when it is so faint it cannot be heard
- Masking: a sound cannot be detected when it is not as loud as the background noise

Audiograms of Marine Life

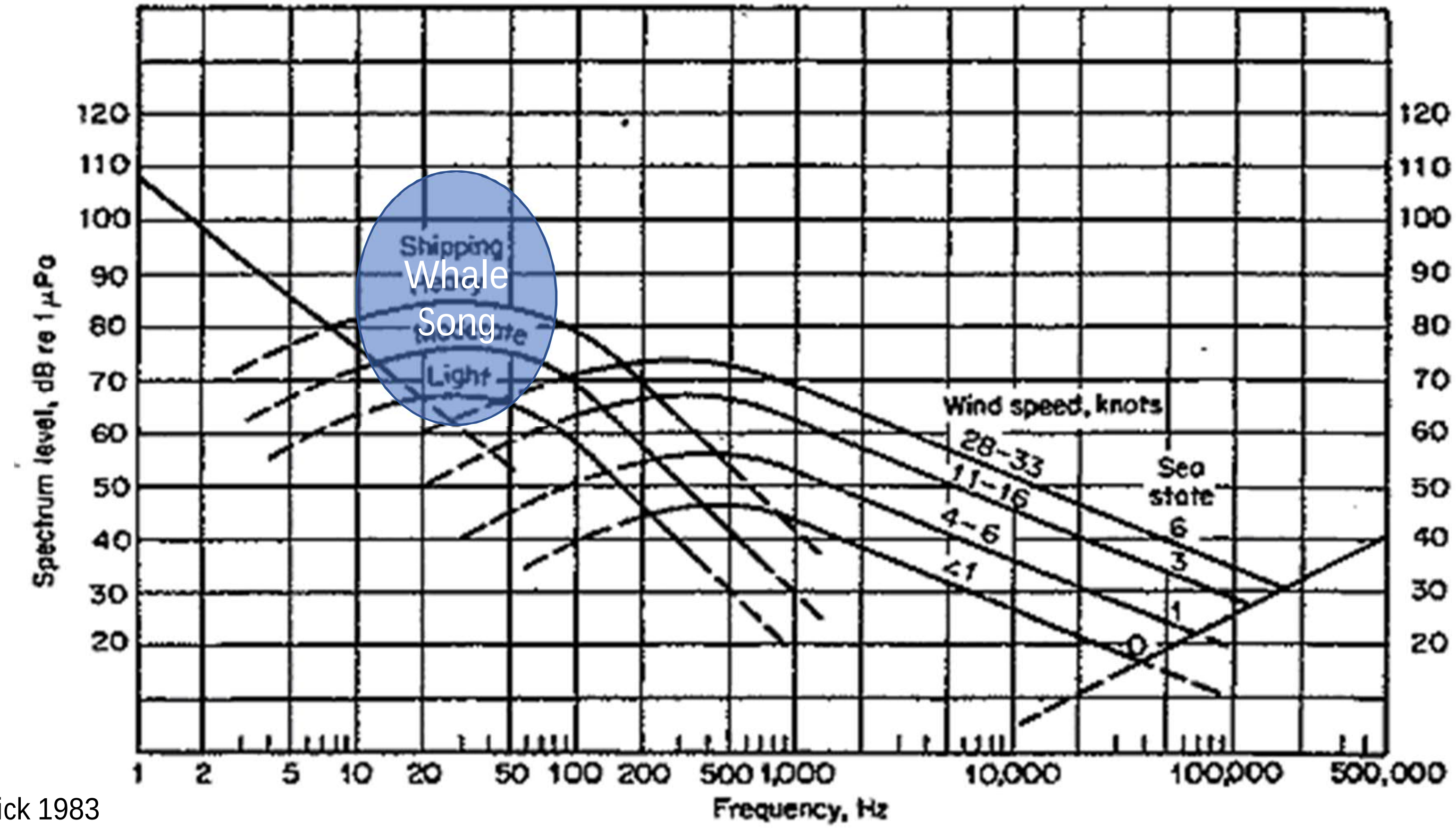


Example of Detection Limited By Hearing: Bottlenose Dolphin Cannot Hear Windmill < 1 kHz



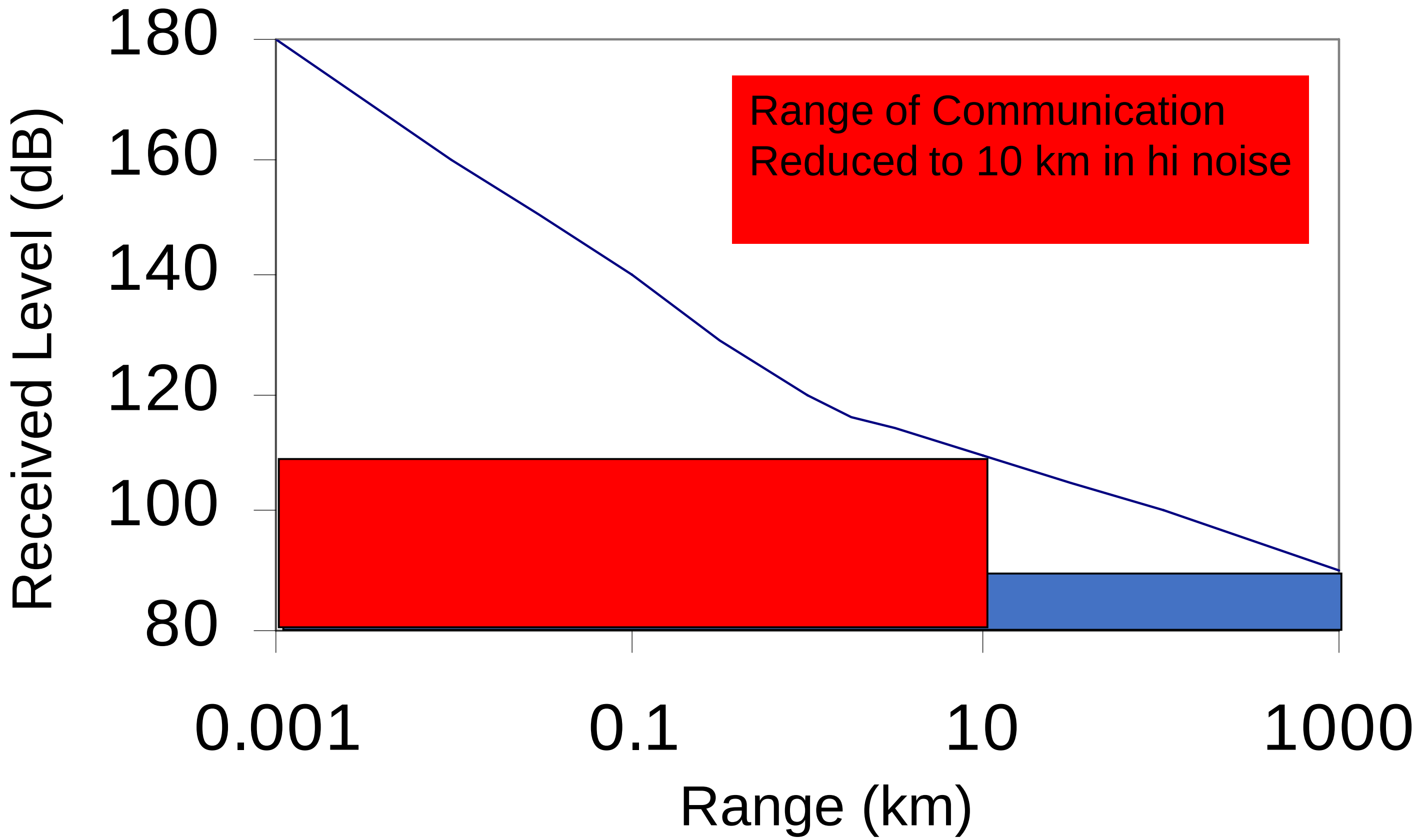
Madsen PT, et al. 2006. *Mar Ecol Prog Ser* 309:279–295

The aggregate sound of thousands of ships dominates average ambient ocean noise 10-200 Hz



Urick 1983

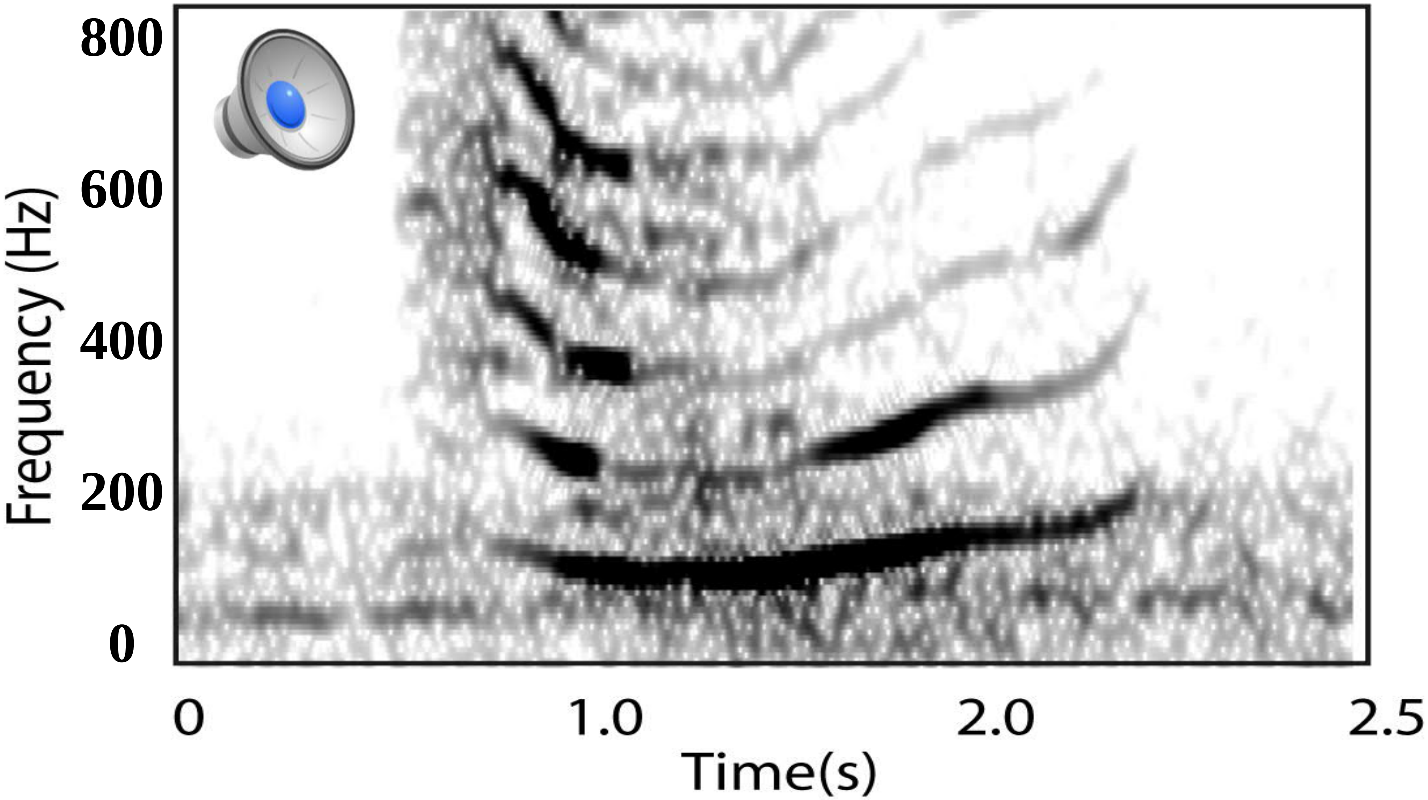
Example of Masking: Increased Noise Can Reduce Effective Range of Communication



Whales do not just tolerate reduced range of communication: they compensate for increased anthropogenic noise

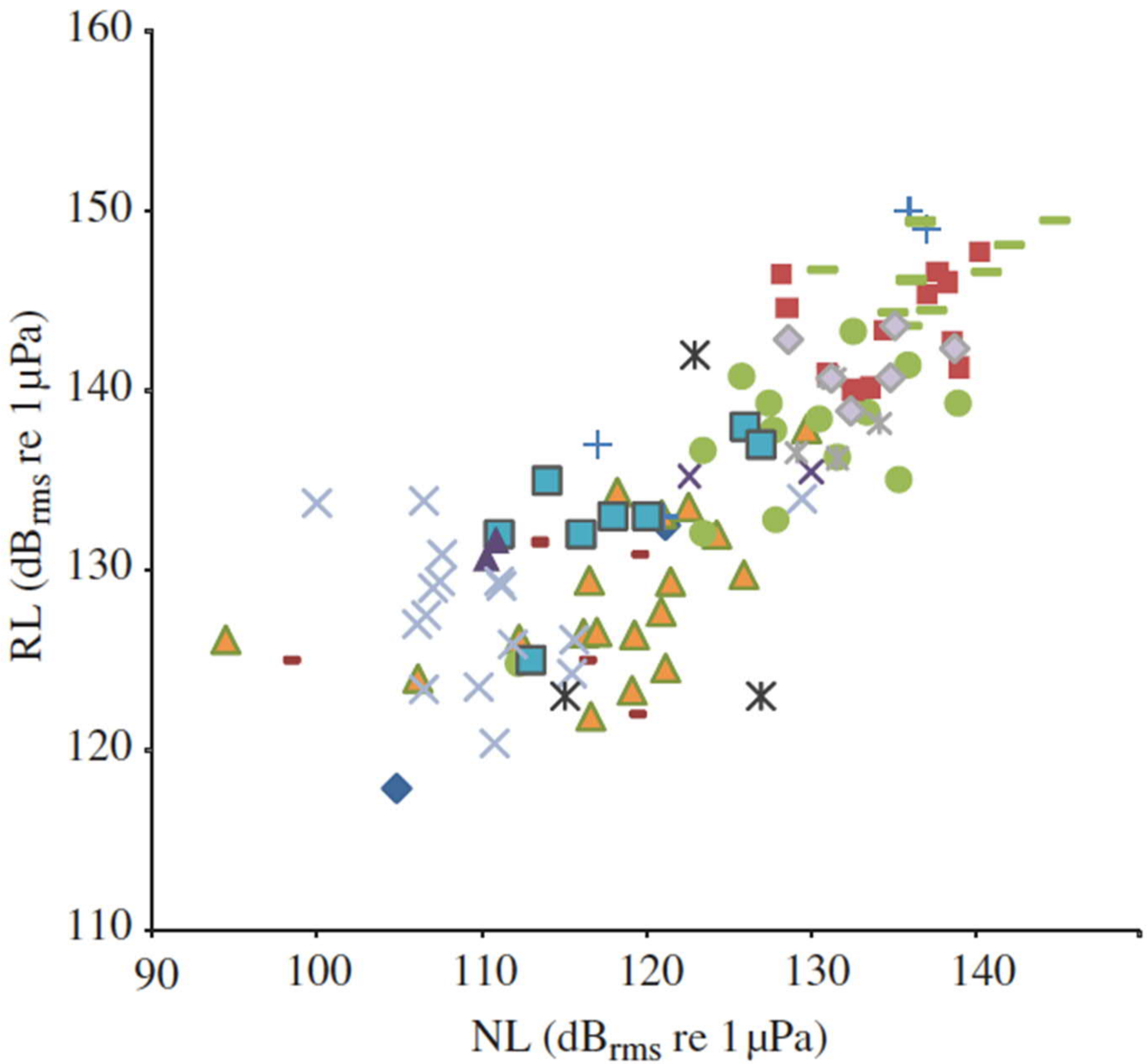
- Increase Source Level
  - Right whale response to shipping noise (Parks 2003 PhD thesis WHOI/MIT)
- Shift Call Frequency out of Noise Band
  - Higher call frequency for right whales exposed to higher shipping noise (Parks et al. 2007 JASA 122, 3725)
- Increase Length of Calls
  - Killer whales respond to whale watching boats (Foote et al. 2004 Nature 428: 910)
- Increase Redundancy of Calls
  - Humpback song response to low frequency naval sonar (Miller et al. 2000 Nature 405:903)

Right Whale Contact Upcall



Used during reunion events, e.g. Mother-calf reunion, male joining a social group

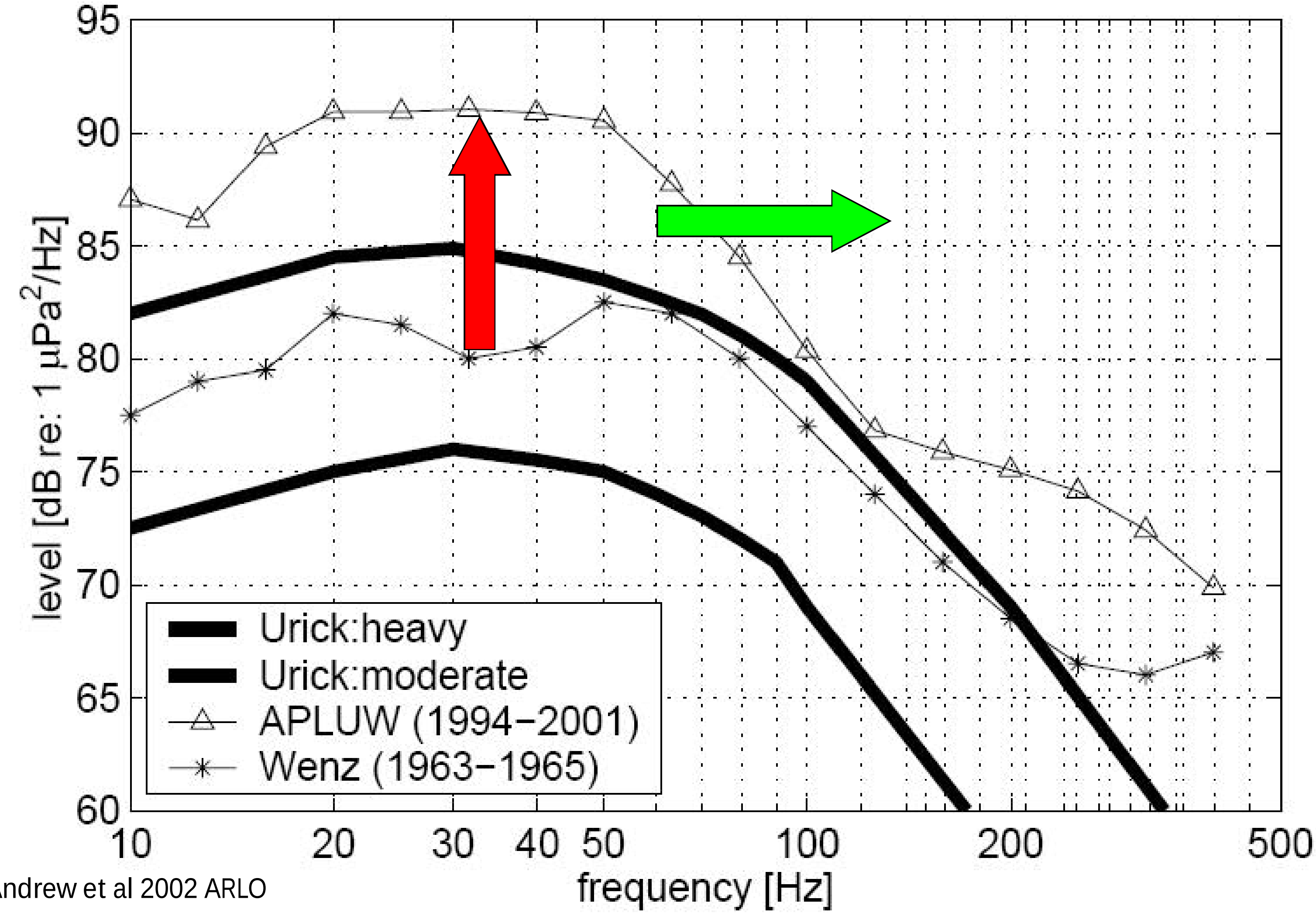
Right Whales Increase the Loudness of their Calls in Increased Noise



Parks et al. 2011 Biol Letters

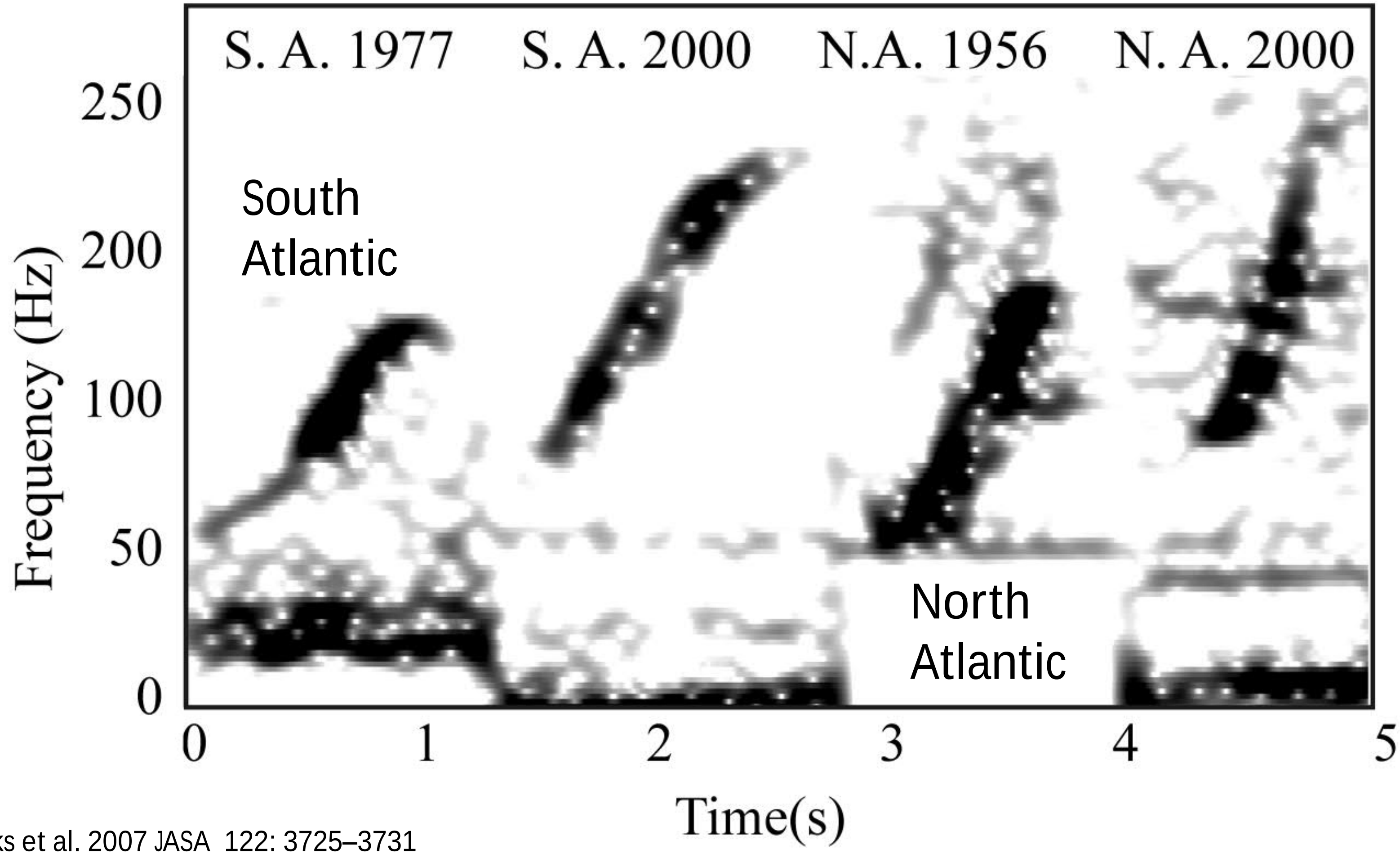
As Low Frequency Noise Increases,

Whales Can Increase Call Frequency Out of Noise Band



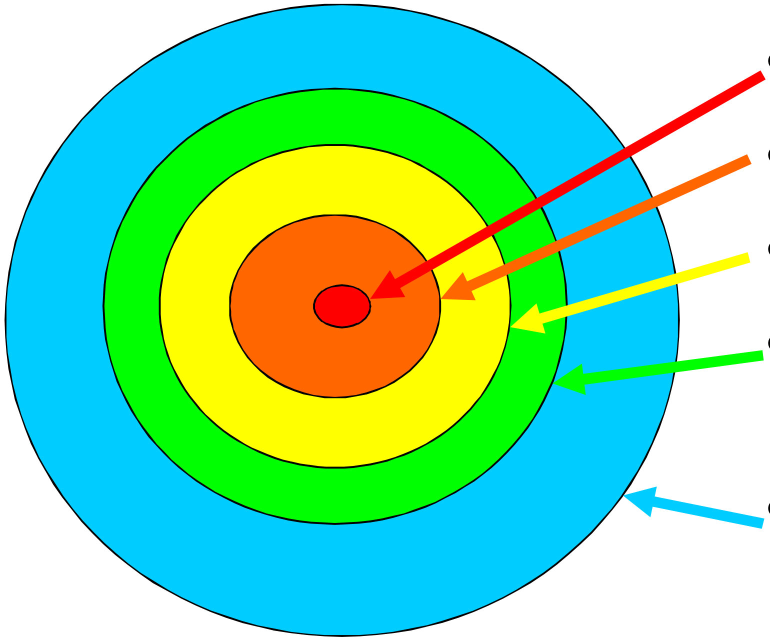
Andrew et al 2002 ARLO

Right Whales Shift Call Frequency Up Away from Shipping Noise



Parks et al. 2007 JASA 122: 3725–3731

Zones of Noise Influence



- Injury
- Hearing Loss
- Avoidance
- Behavioral disturbance
- Audibility (could occur whenever sound level above ambient noise)

Adapted from Richardson and Malme 1995

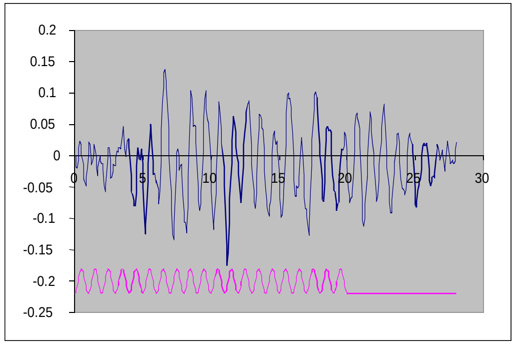
Effects of Sound on Marine Life

(taking off from Ecological Relevance section of Merchant, N. D., Farcas, A., Powell, C. F. (2018) Acoustic metric specification. Report of the EU INTERREG Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS).

- Masking – note the need to account for compensation
- Hearing Loss – temporary threshold shift
- Behavioural responses
- Mortality
- Physiological Stress
- What is the baseline for effects?
- Chronic effects
- Cumulative Impacts

Measuring Temporary Threshold Shift (TTS) in Marine Mammals

- Measure the threshold at which animal just detects a sound
- Expose animal to loud sound
- Measure hearing again to see if threshold shifted

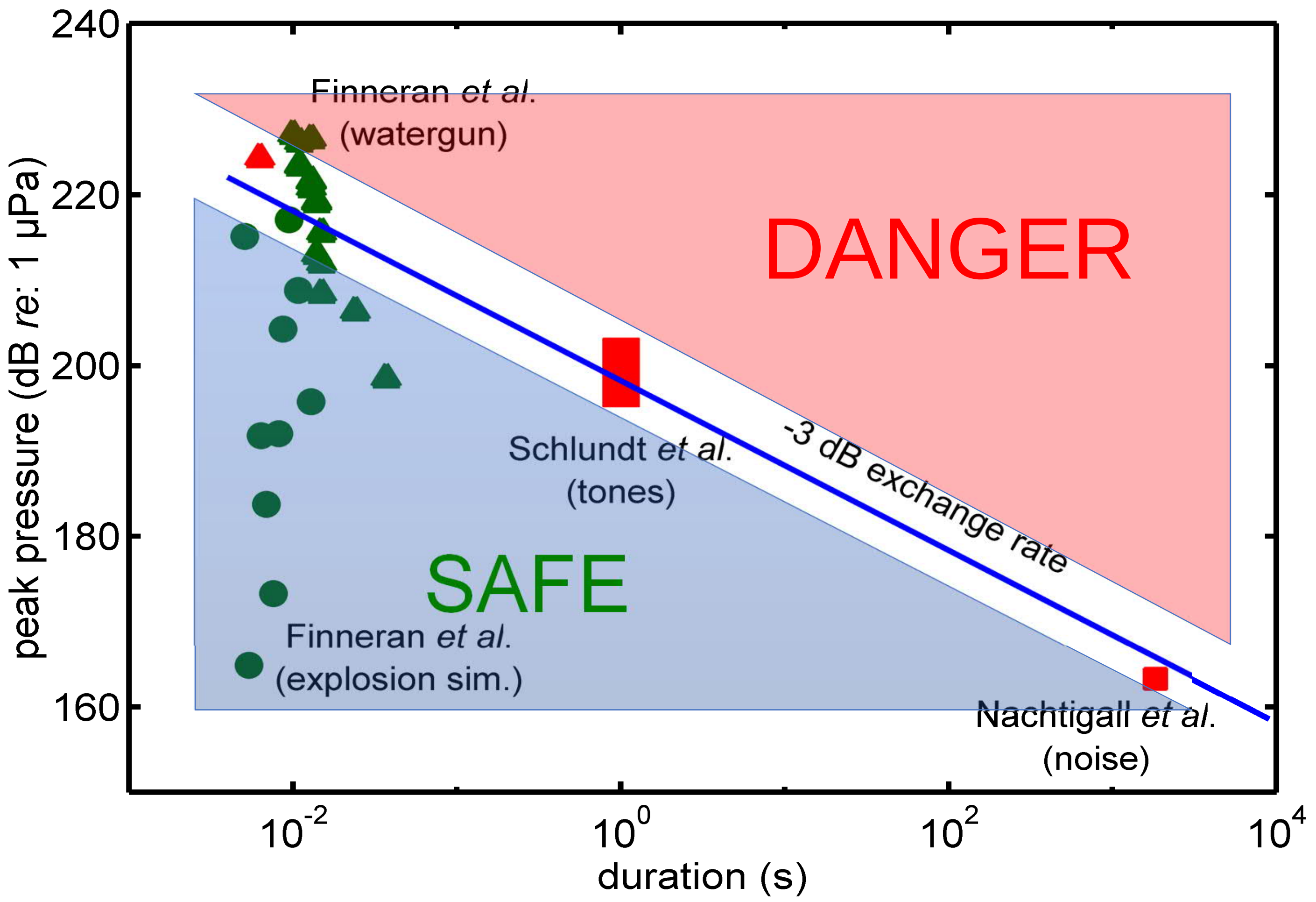


Envelope Following

Nachtigall Univ of Hawaii

Summary of TTS for captive odontocetes

Courtesy J. Finneran



Acoustic Exposure Criteria for TTS

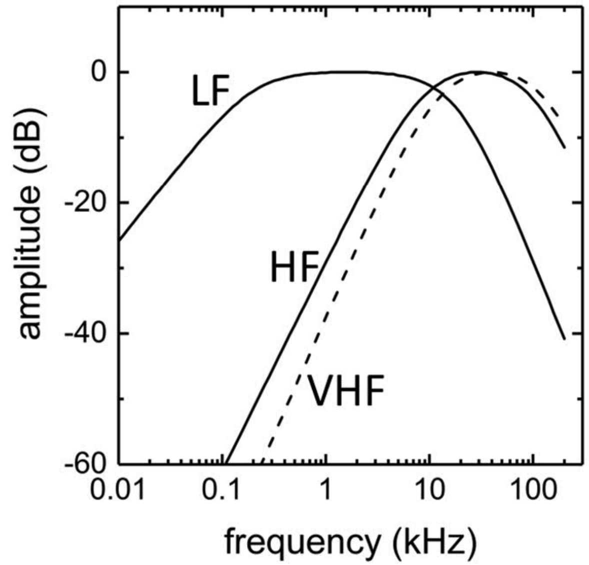
How to estimate from JOMOPANS or MSFD criteria?

Table 3. Proposed injury criteria for individual marine mammals exposed to "discrete" noise events (either single or multiple exposures within a 24-h period; see Chapter 2)

Marine mammal group	Sound type		
	Single pulses	Multiple pulses	Nonpulses
Low-frequency cetaceans	Cell 1	Cell 2	Cell 3
Sound pressure level	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)
Sound exposure level	198 dB re: 1 µPa²-s (M_{lf})	198 dB re: 1 µPa²-s (M_{lf})	215 dB re: 1 µPa²-s (M_{lf})
Mid-frequency cetaceans	Cell 4	Cell 5	Cell 6
Sound pressure level	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)
Sound exposure level	198 dB re: 1 µPa²-s (M_{mf})	198 dB re: 1 µPa²-s (M_{mf})	215 dB re: 1 µPa²-s (M_{mf})
High-frequency cetaceans	Cell 7	Cell 8	Cell 9
Sound pressure level	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)	230 dB re: 1 µPa (peak) (flat)
Sound exposure level	198 dB re: 1 µPa²-s (M_{hf})	198 dB re: 1 µPa²-s (M_{hf})	215 dB re: 1 µPa²-s (M_{hf})
Pinnipeds (in water)	Cell 10	Cell 11	Cell 12
Sound pressure level	218 dB re: 1 µPa (peak) (flat)	218 dB re: 1 µPa (peak) (flat)	218 dB re: 1 µPa (peak) (flat)
Sound exposure level	186 dB re: 1 µPa²-s (M_{pw})	186 dB re: 1 µPa²-s (M_{pw})	203 dB re: 1 µPa²-s (M_{pw})
Pinnipeds (in air)	Cell 13	Cell 14	Cell 15
Sound pressure level	149 dB re: 20 µPa (peak) (flat)	149 dB re: 20 µPa (peak) (flat)	149 dB re: 20 µPa (peak) (flat)
Sound exposure level	144 dB re: (20 µPa)²-s (M_{pa})	144 dB re: (20 µPa)²-s (M_{pa})	144.5 dB re: (20 µPa)²-s (M_{pa})

From Southall et al. (2007) Marine Mammal Noise Exposure Criteria: Initial Scientific Recommendations. Aquatic Mammals, 33(4), ISSN 0167-5427

AUDITORY WEIGHTING FUNCTIONS



Southall et al. (2019) Marine Mammal Noise Exposure Criteria:Updated Scientific Recommendations for Residual Hearing Effects. Aquatic Mammals, 45(2), 125-232, DOI 10.1578/AM.45.2.2019.125

Effective Quiet

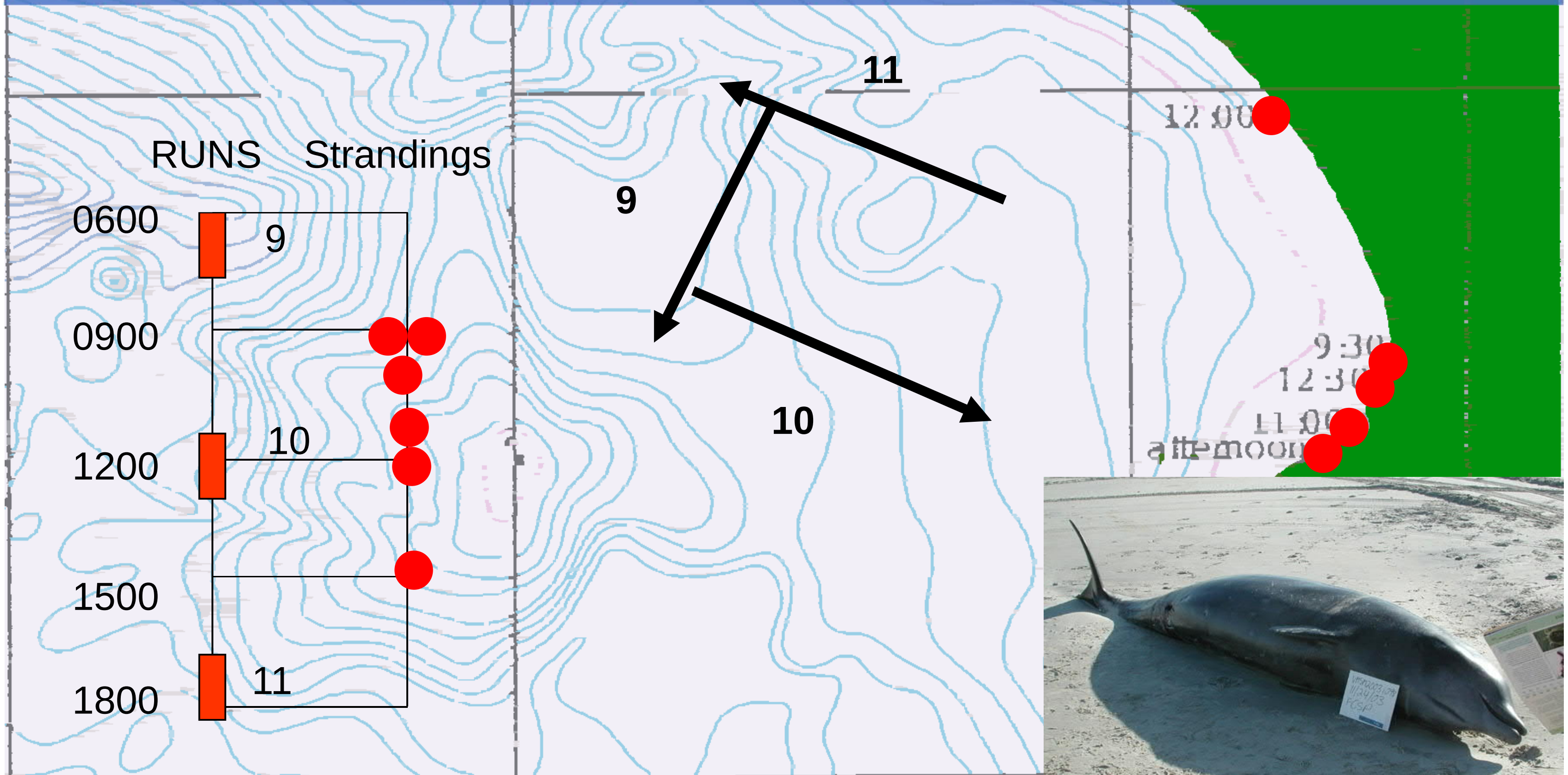
- Ward et al. (2006) argue that effective quiet (EQ) is the level of sound quiet enough to allow recovery from TTS.
- The quieter below EQ, the more rapid the recovery from TTS.
- To estimate recovery from TTS, noise measurements need to monitor the continuous duration of EQ.
- Just reporting the distribution of NLs is not enough

Ward et al. 2006 Effective quiet and moderate TTS: implications for noise exposure standards. JASA 59:160

Behavioural Effects of Noise: A deep dive into an Unexpected Source of Injury

- >10 Beaked whales strand within a few hours in dispersed groupings over tens of km of shore.
- By 2009 reported to coincide with naval maneuvers off Greece (1), Canary Islands (7), Italy (2), Bahamas (1), Madeira (1)
- All known cases involve ships with mid-frequency (MF: 2-10 kHz) sonars

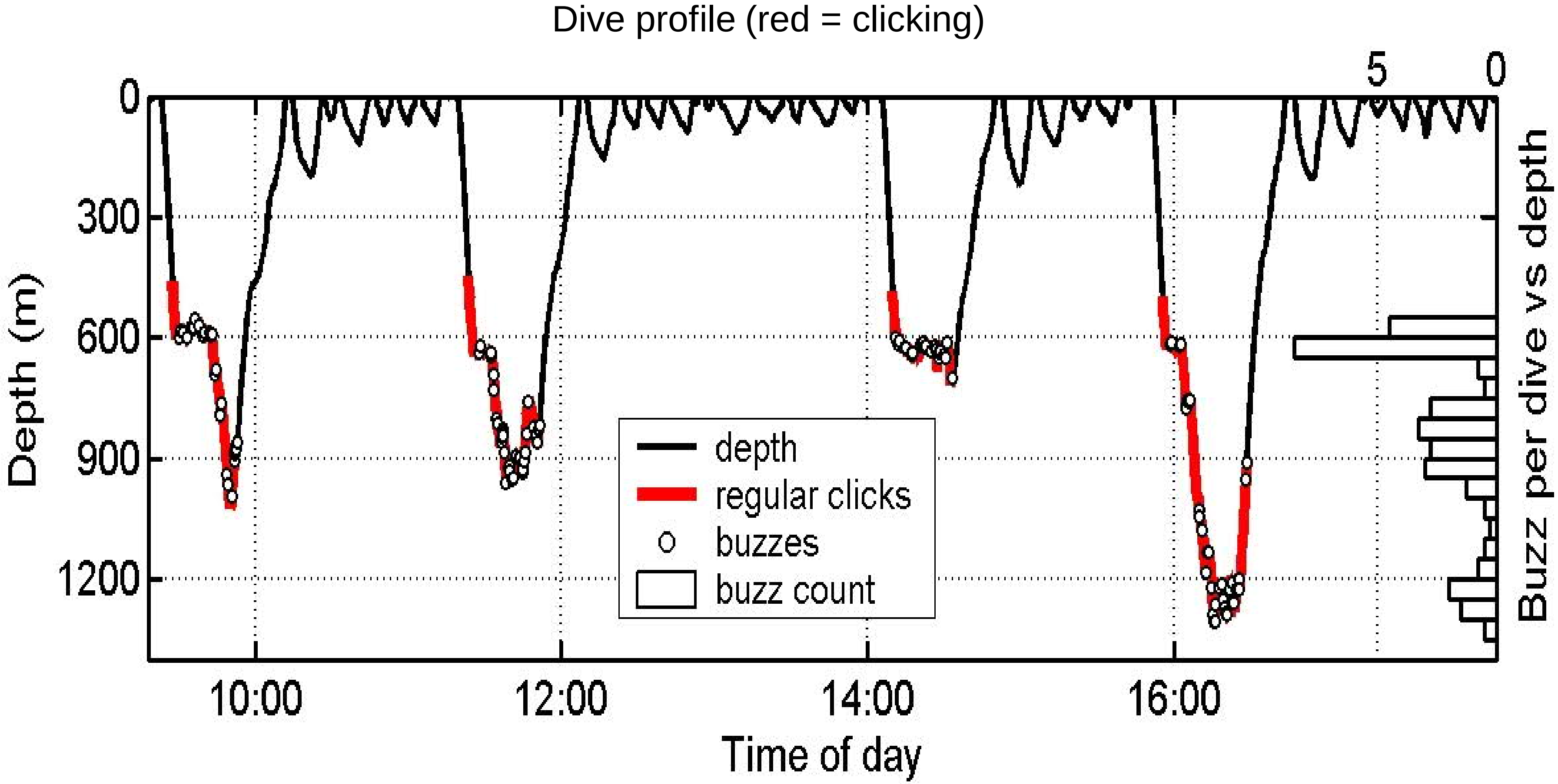
Example of mass strandings of beaked whales coincident with sonar exercises on W coast of Greece



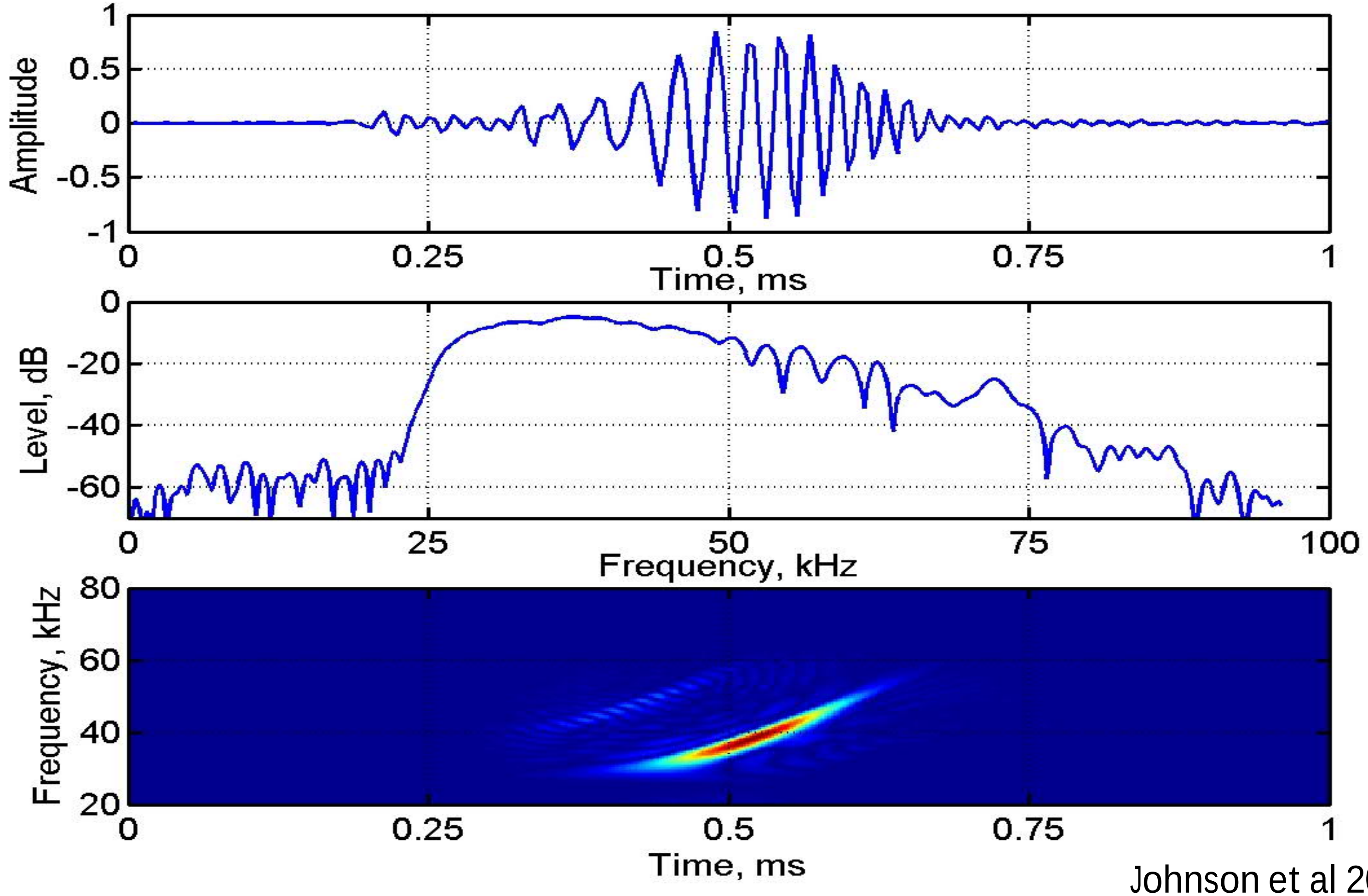
D'Amico 1998 Saclantcen M-133


Tagging Beaked Whales to Study
Baseline Behaviour

Beaked whales echolocate for food in deep dives

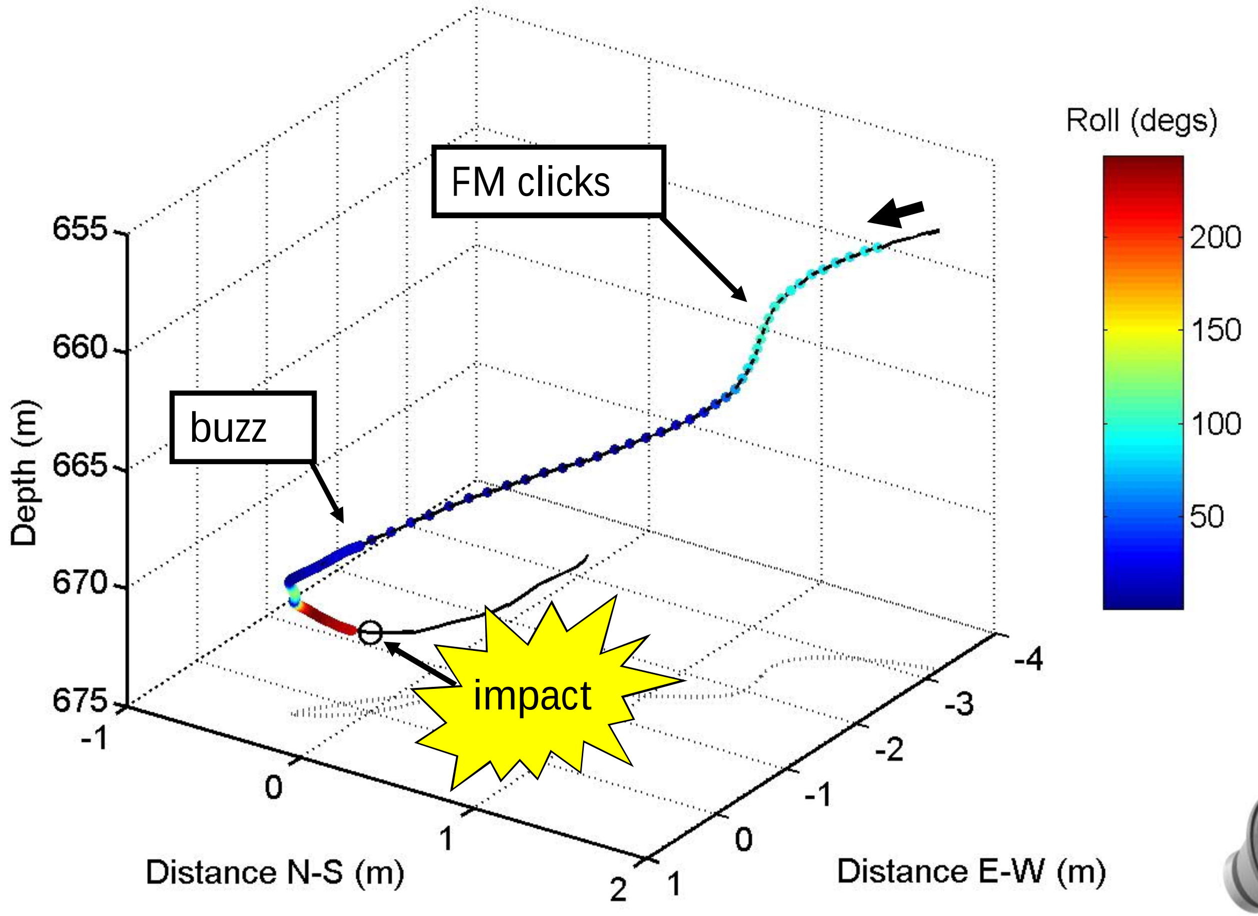


Beaked Whale Click

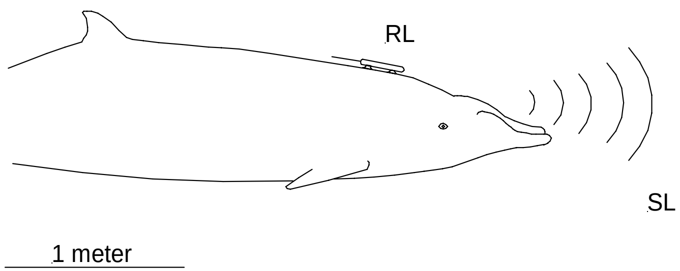


Johnson et al 2009

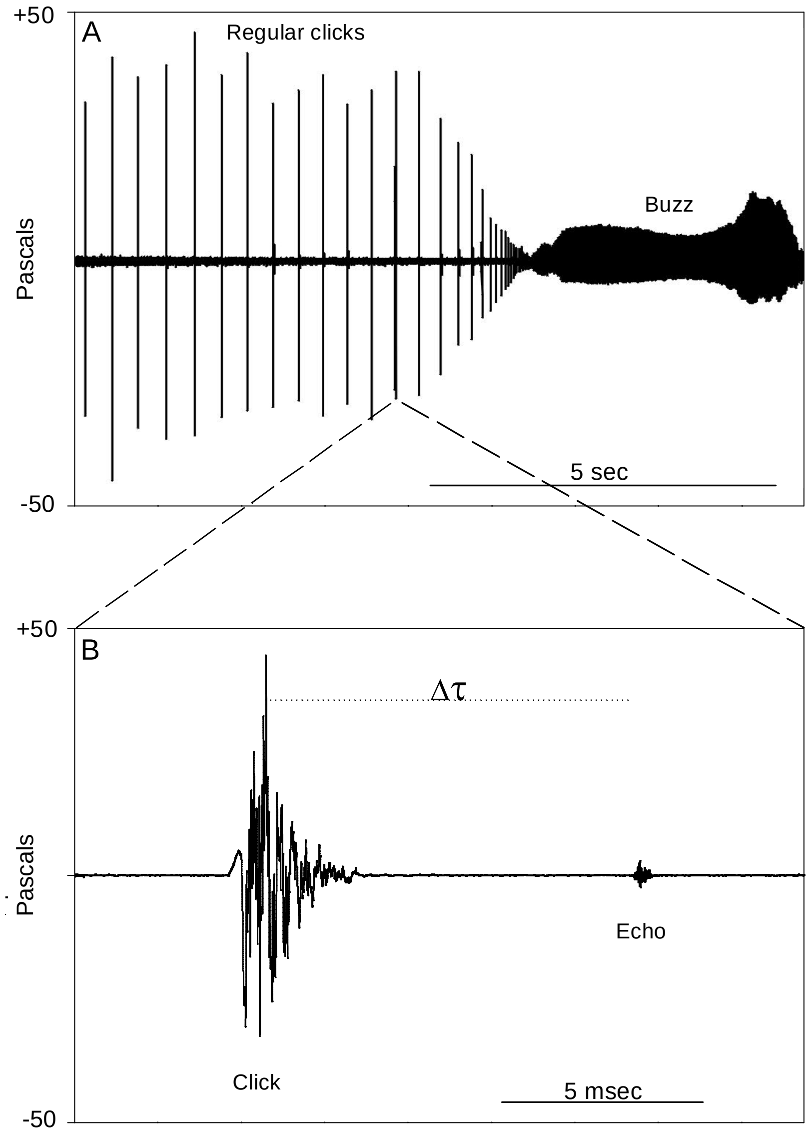
Sudden movements occur at buzzes



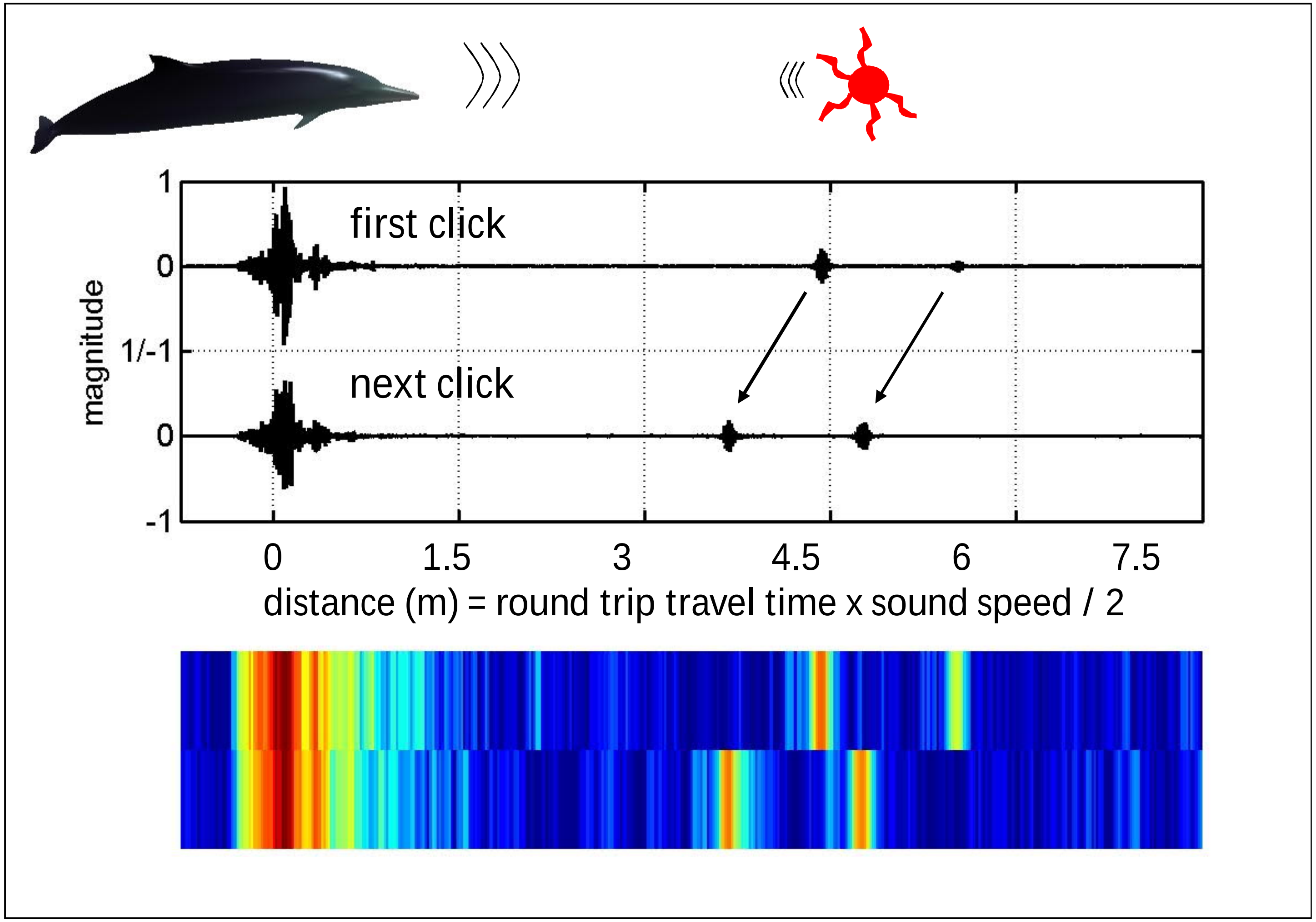
Beaked Whales echolocate on prey



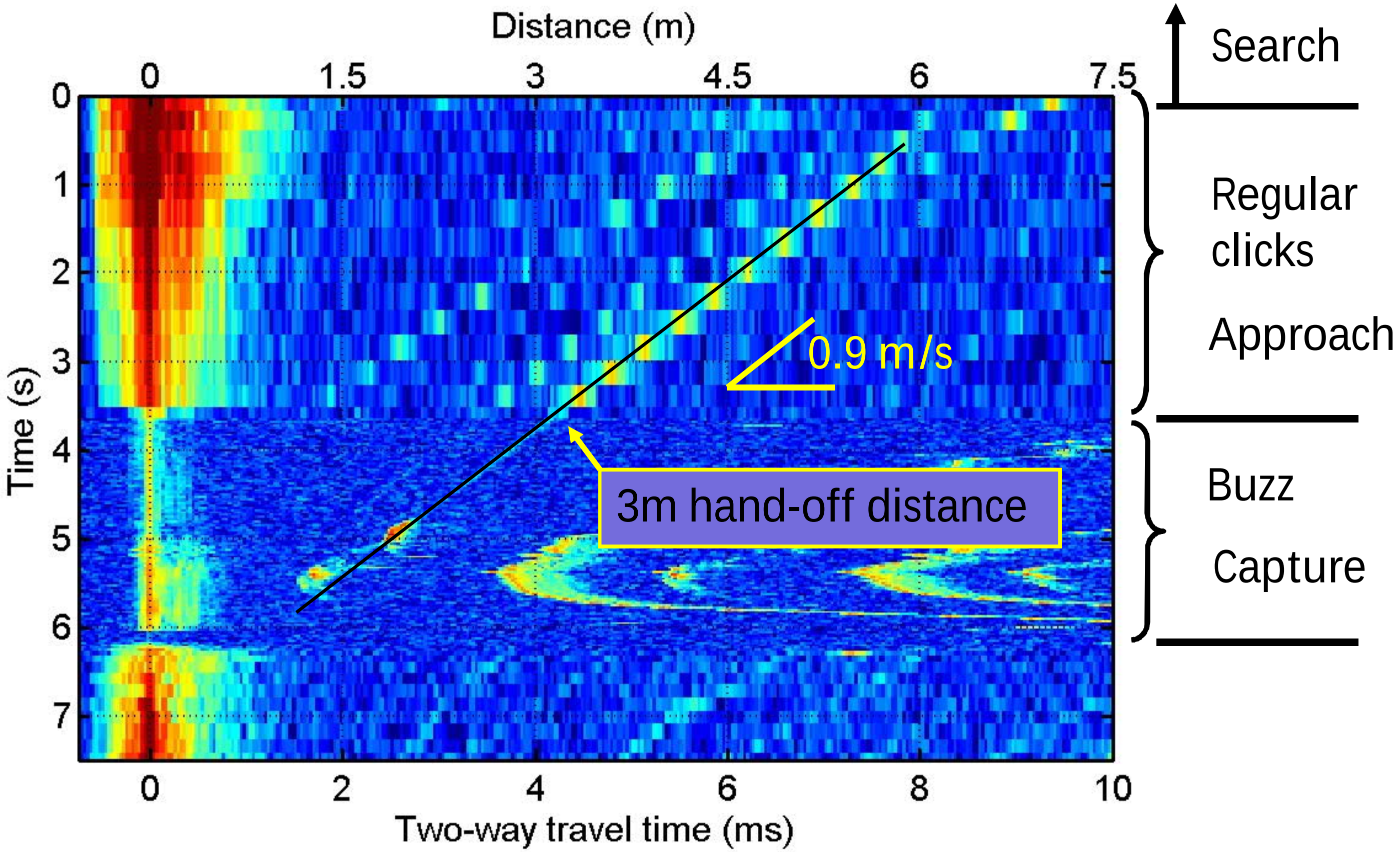
Madsen et al. 2005



Echoes from targets are recorded by the tag



Echogram of click sequence continuing into a buzz

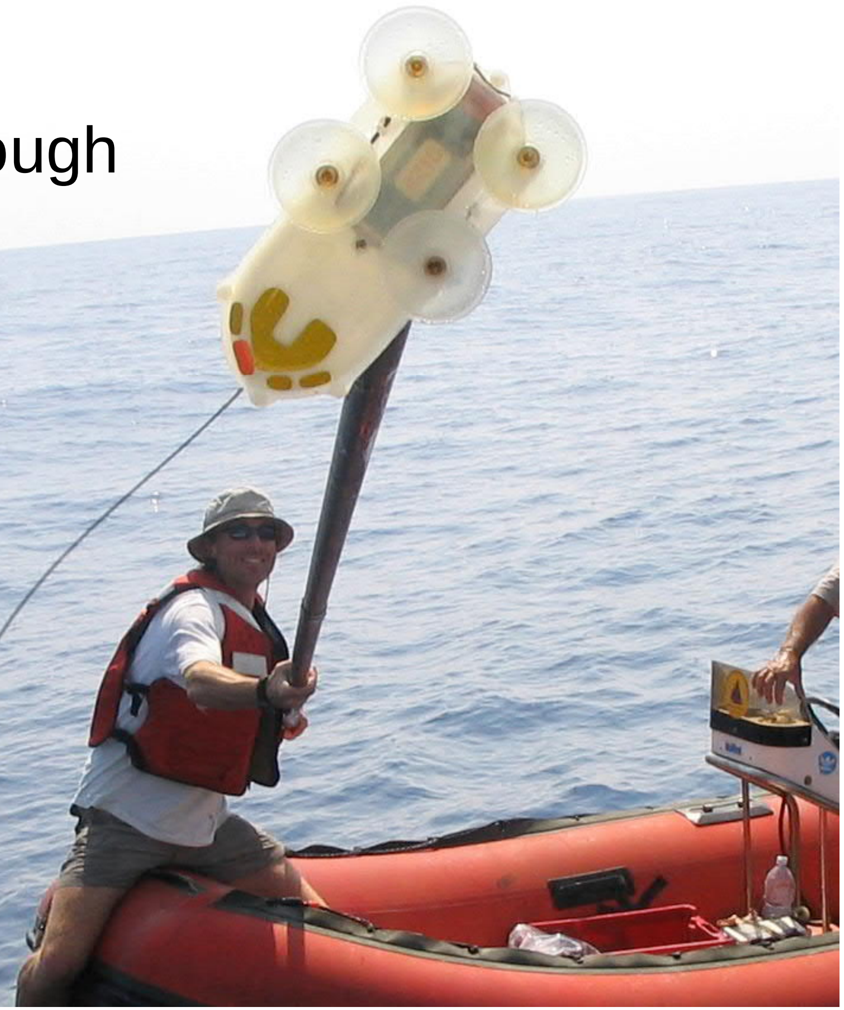


Behavioural Response Studies

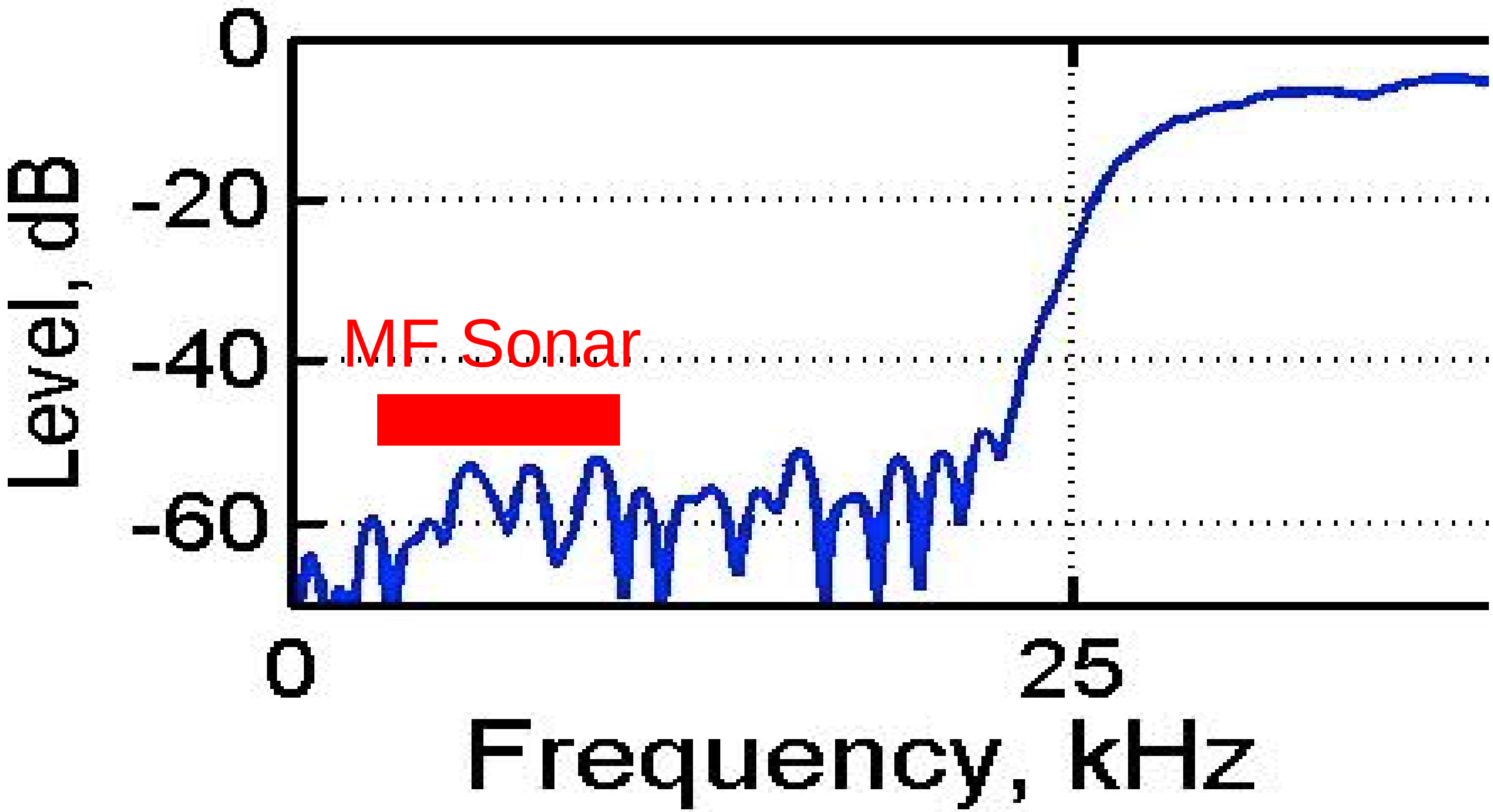
- Develop experiments to safely test responses of whales to sound
- Define response from beaked whales to sonar that is safe but can be used to indicate risk
- Establish acoustic exposures (and other contexts) required to evoke the response

For Behavioral Experiment, Individual Whale must be used as own Control

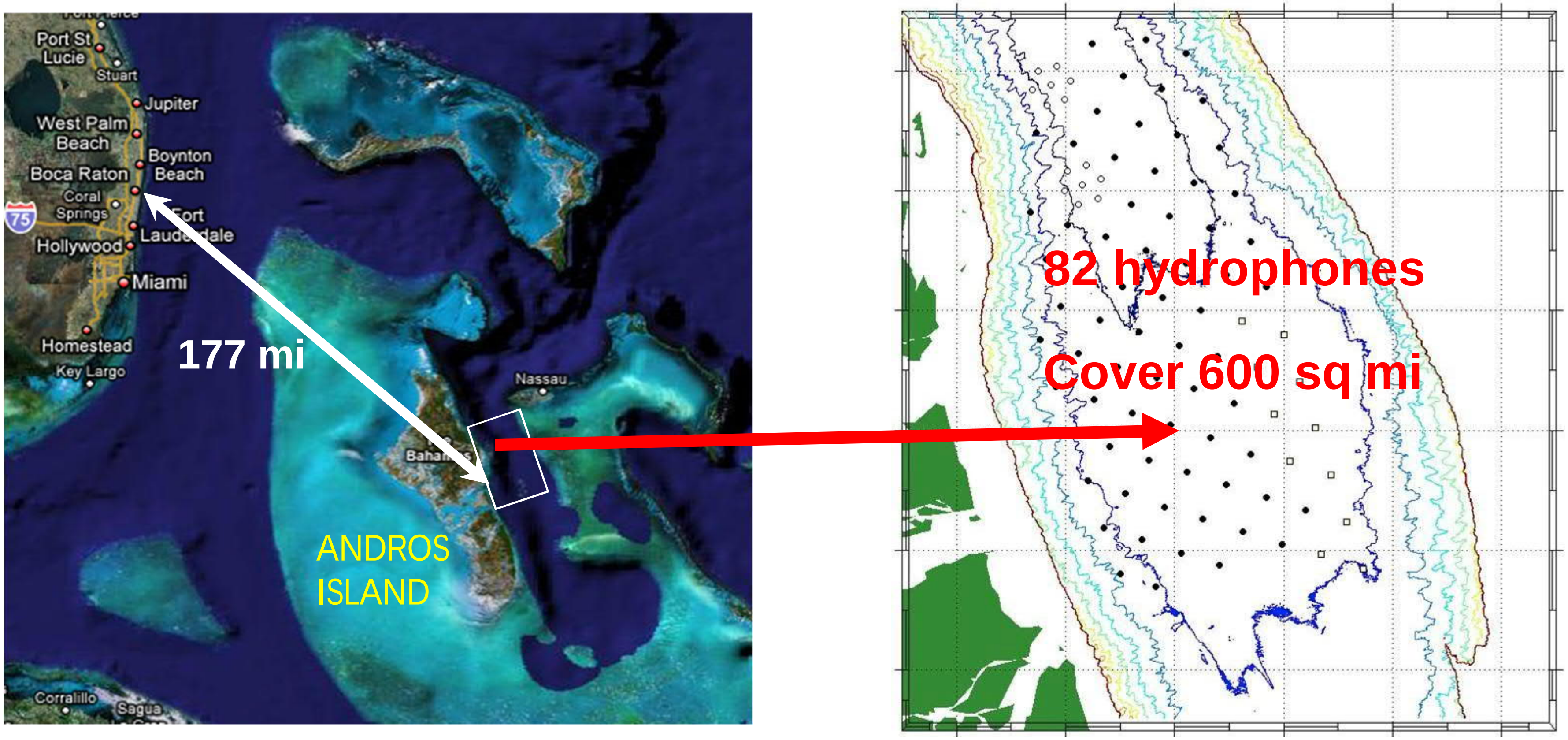
- Tag attached for long enough to obtain pre-exposure baseline, exposure responses, and post-exposure recovery
- Tag designed for ~1day attachments



No overlap in frequency between the sounds used by beaked whales and mid-frequency naval sonars

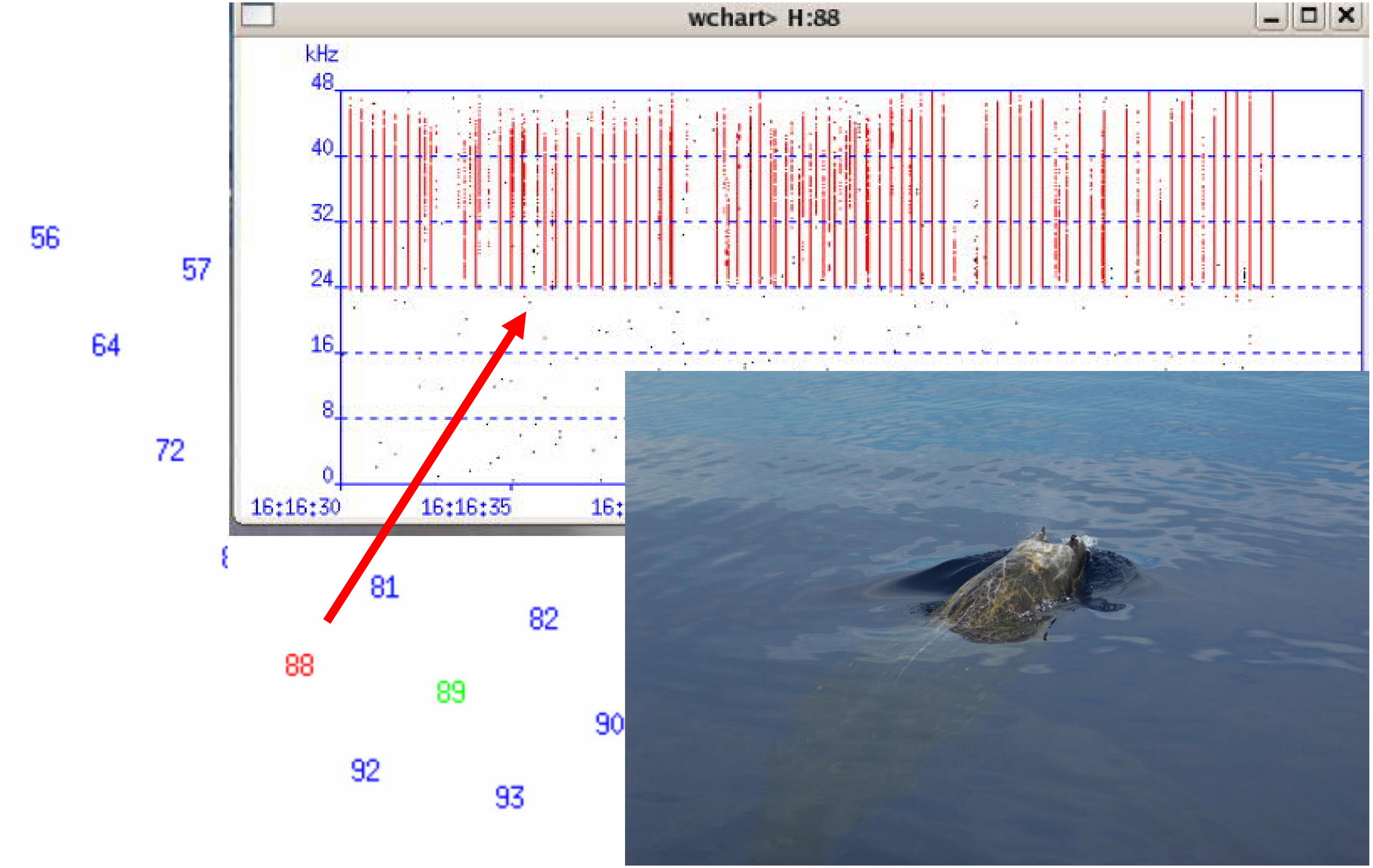


Real time passive acoustic monitoring of beaked whales using AUTEC hydrophone array

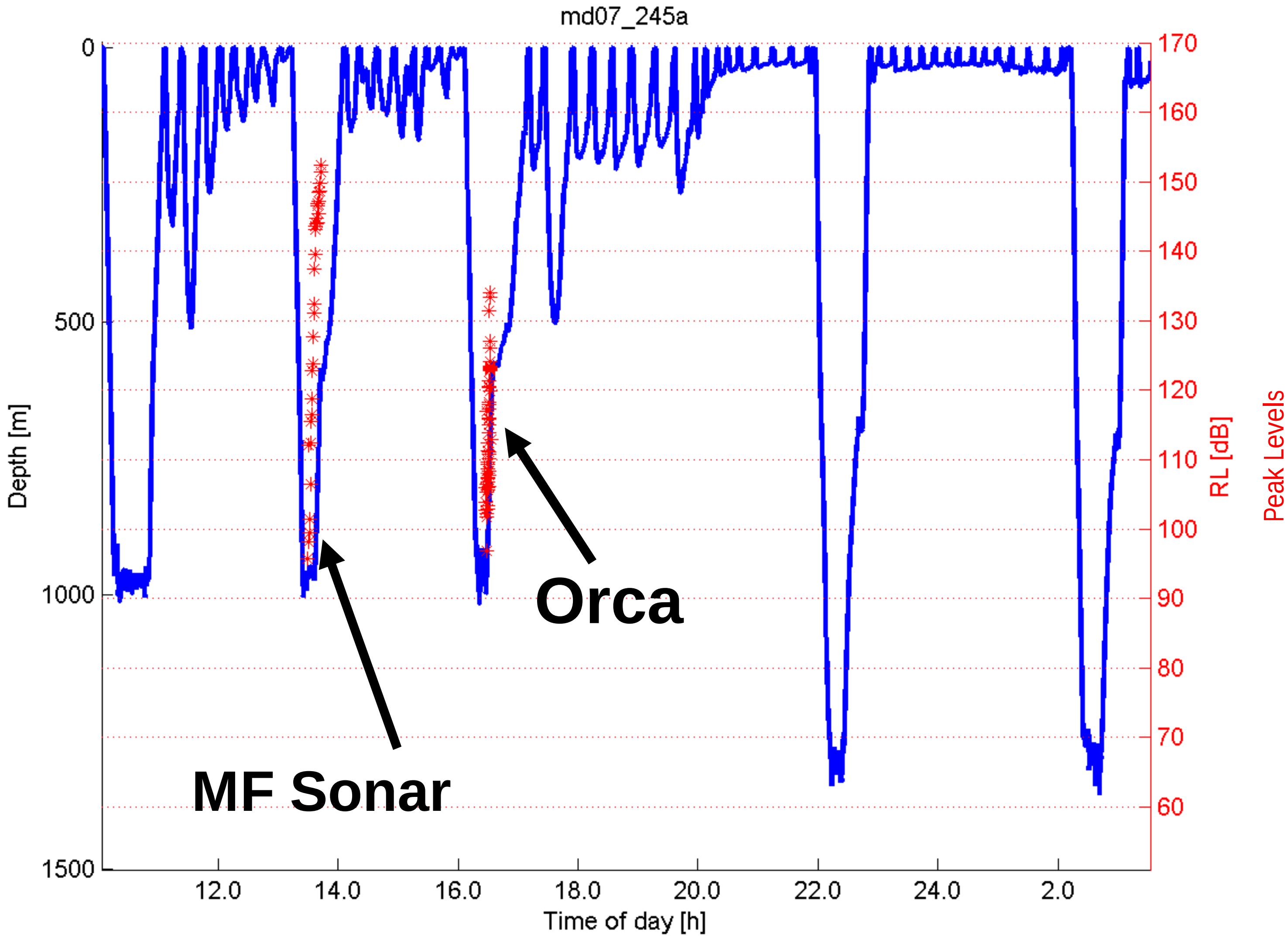


Collaboration with David Moretti, NUWC

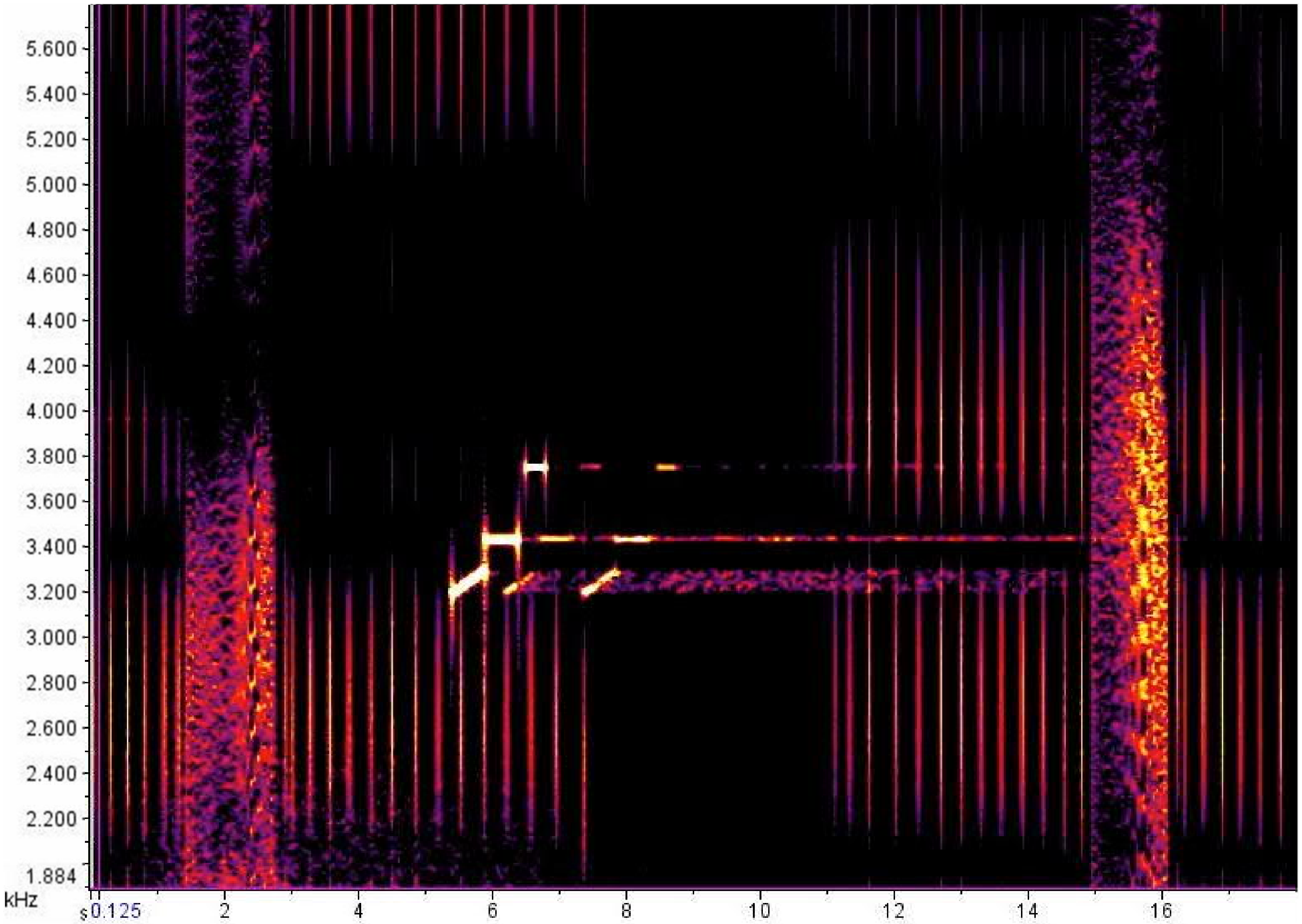
Marine Mammal Monitoring @ AUTEC



Received Level of Playbacks to *Mesoplodon densirostris*



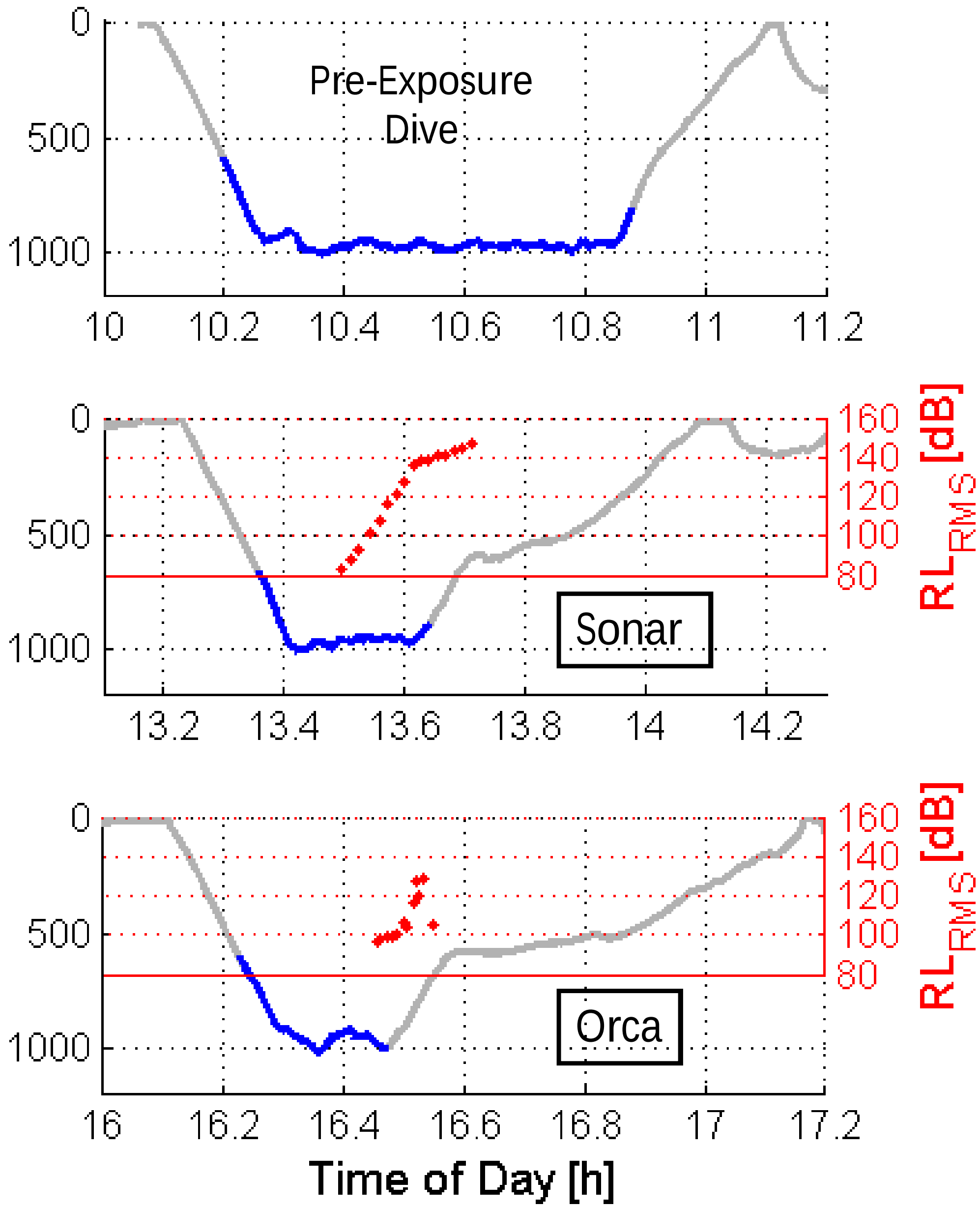
Naval Sonar as recorded on Dtagged Whale

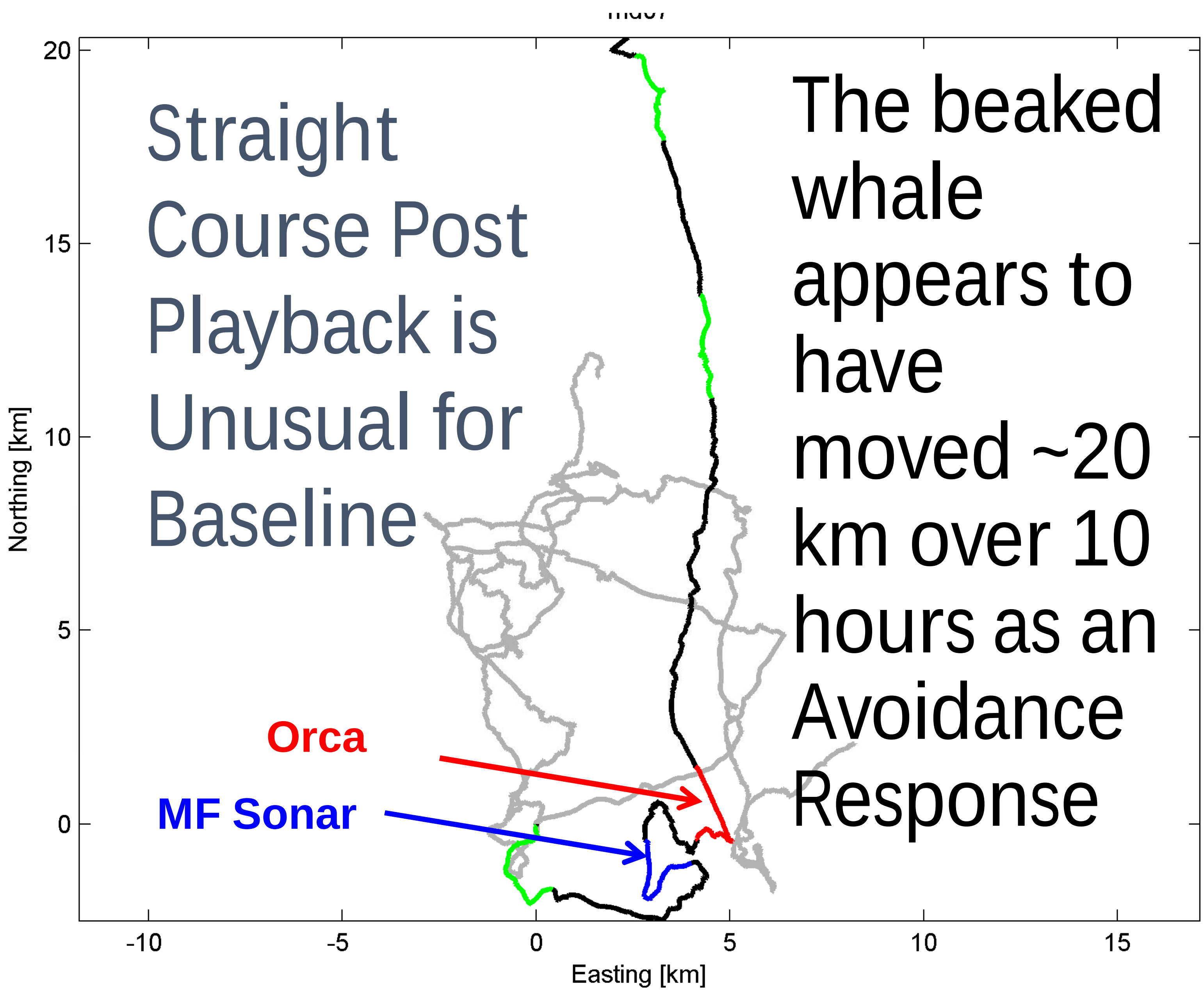


Time in seconds

Beaked Whales exposed to Playback Prematurely Stop Clicking and Make a Long, Slow Ascent

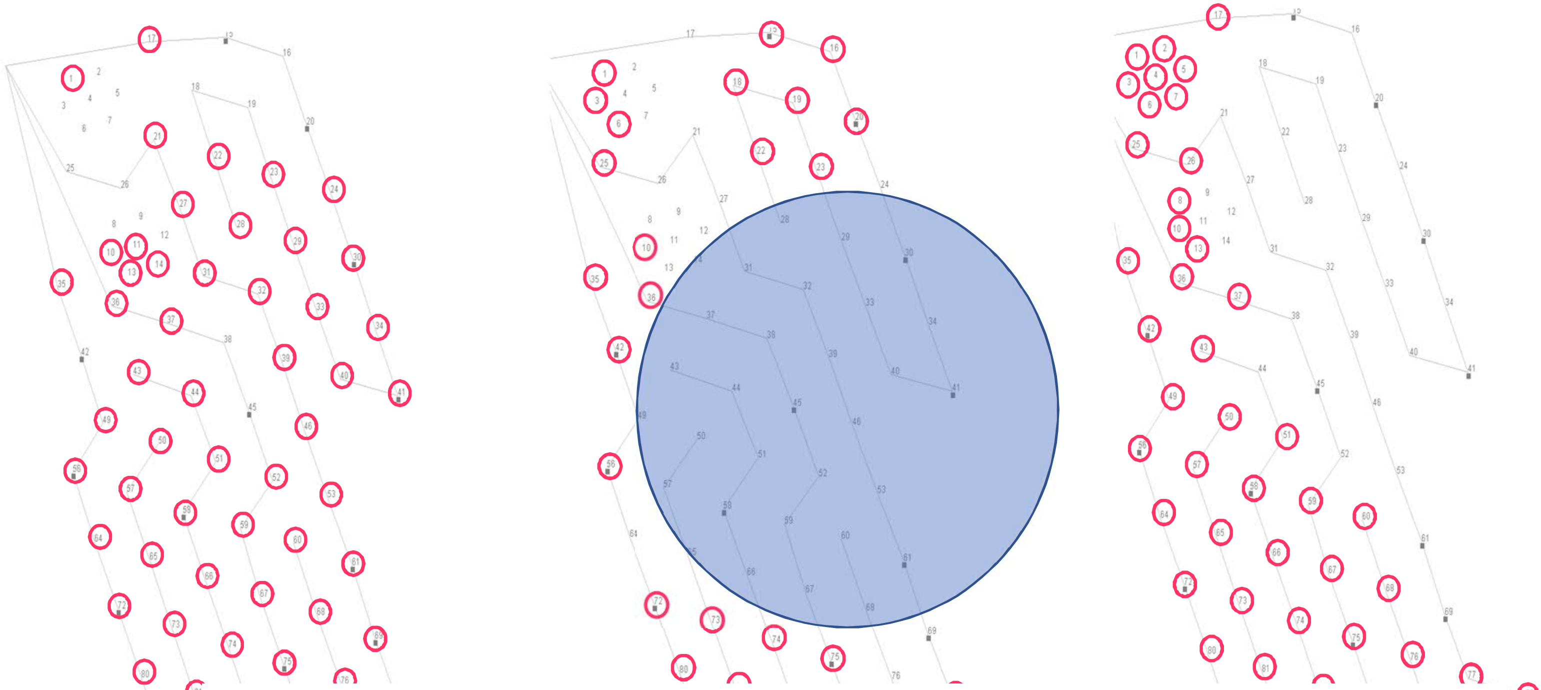
Blainville's Beaked Whale
Mesoplodon densirostris




Straight Course Post Playback is Unusual for Baseline
The beaked whale appears to have moved ~20 km over 10 hours as an Avoidance Response
Orca
MF Sonar
Northing [km]
Easting [km]
20
15
10
5
0
-10
-5
0
5
10
15

NAVSEA NEWPORT
Undersea Warfare Center Division

Distribution of Blainville's Beaked Whale Vocalizations Before, During, After Active Sonar Operations



EFFECT RANGE ~10 KM. CORRESPONDING RECEIVED LEVEL ~ 155 dB (235 – 20 log (10000))

Record Duration= 19:39 hours:min
Groups on Range= 56
Vocal Duration (min)

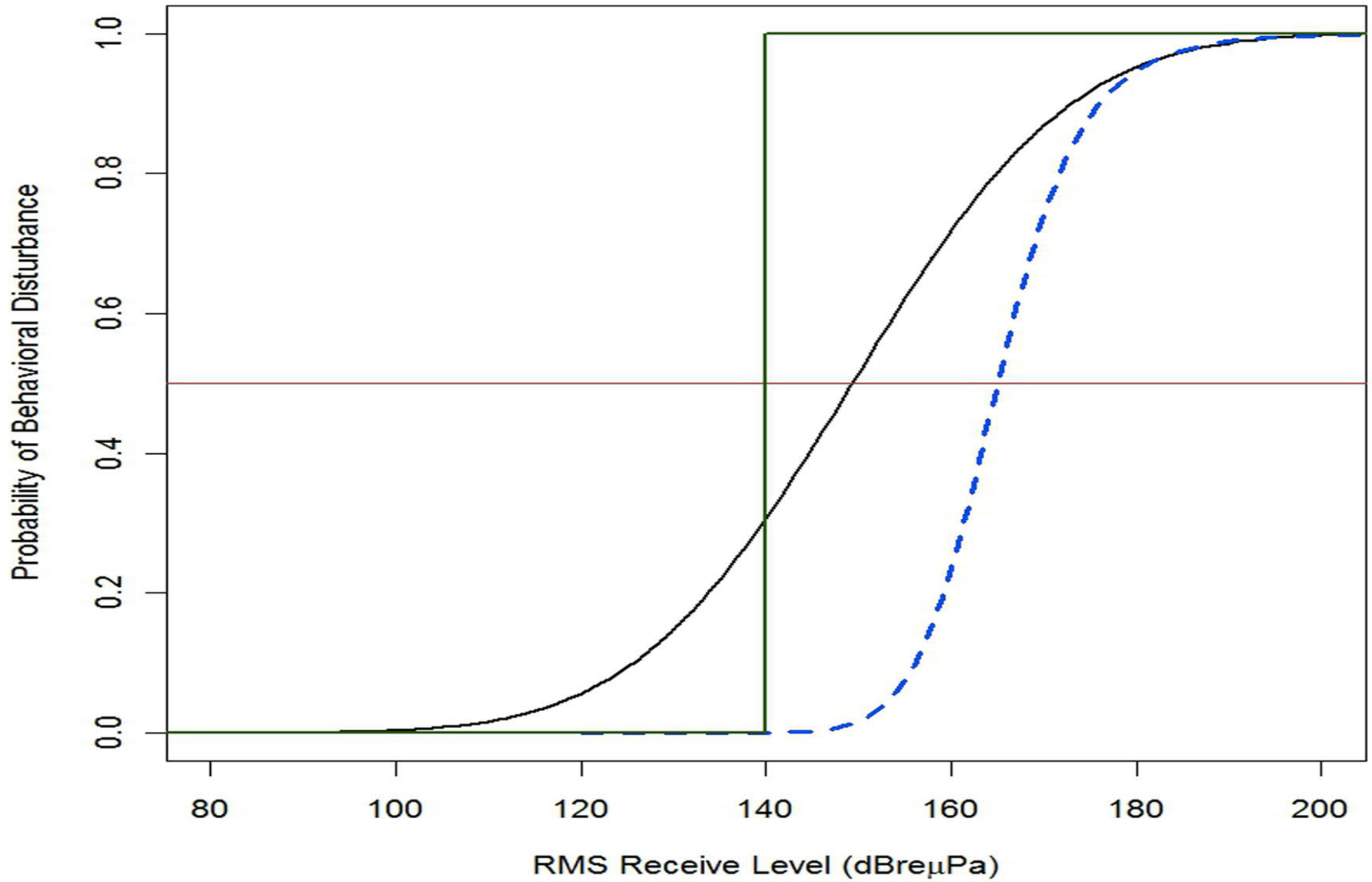
Mean	32.56
Max	49
Min	11
Stand Dev	9.05

Record Duration= 22:56 hours:min
Groups on Range= 36
Vocal Duration(min)

Mean	20.42
Max	32
Min	2
Stand Dev	8.58

Record Duration= 22:01 hours:min
Groups on Range= 50
Vocal Duration (min)
Mean= 29.76
Max= 50
Min= 7
Stand Dev= 8.45

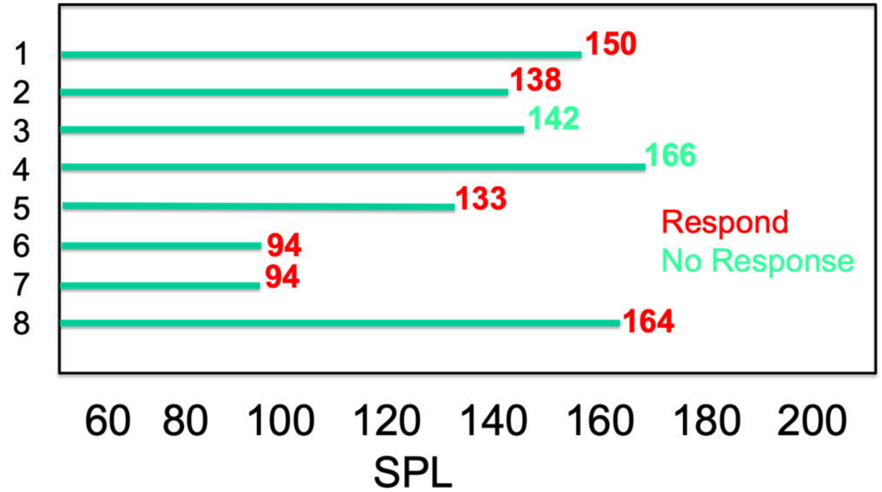
Disturbance Function for Mesoplodon during Sonar Exercises

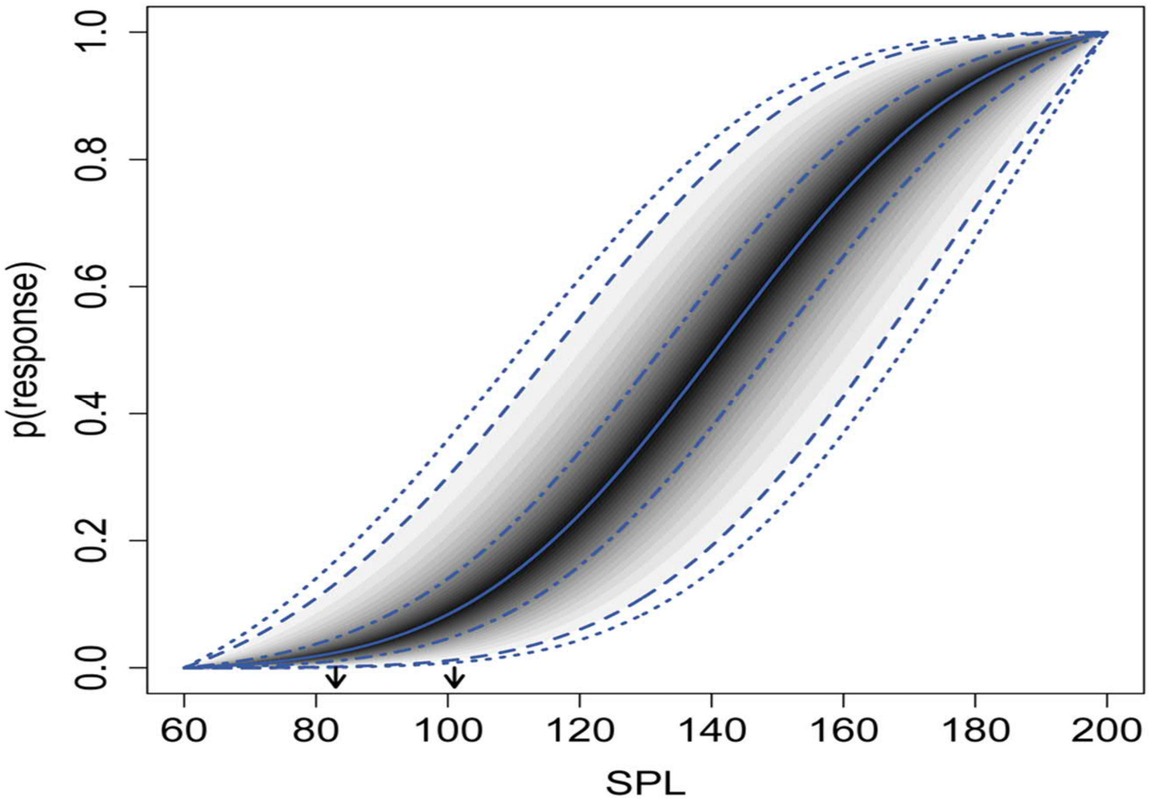


Moretti et al. (2014) PlosOne

Development of Probabilistic Dose:Response Functions

Avoidance Responses of Killer Whales to Sonar



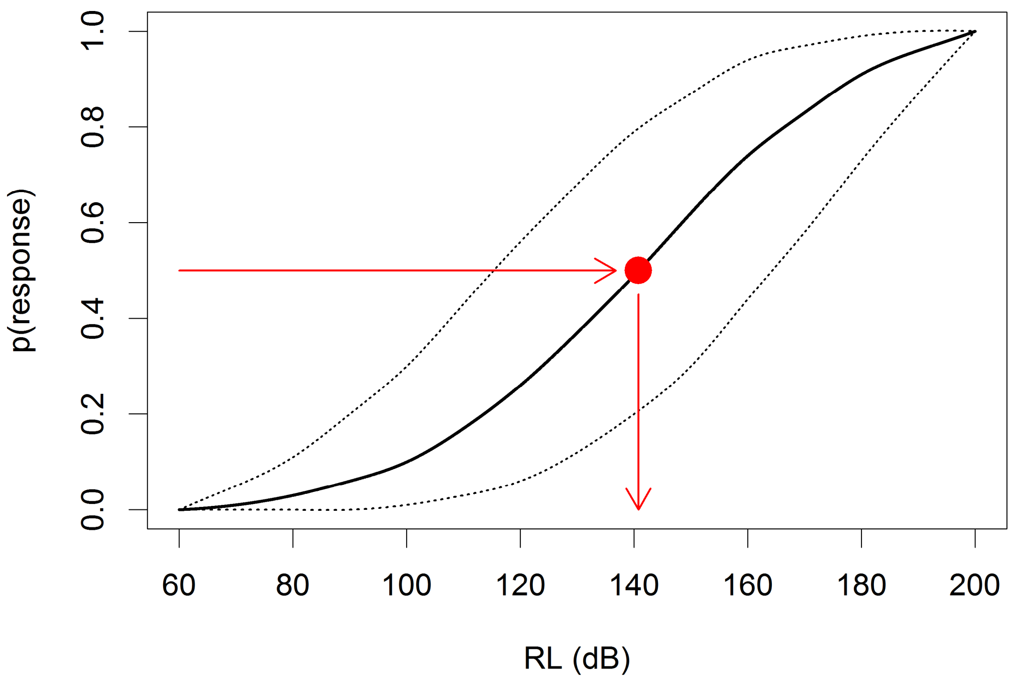


Miller et al. (2014) JASA 135:975

Estimating the number of animals affected from a dose:response function

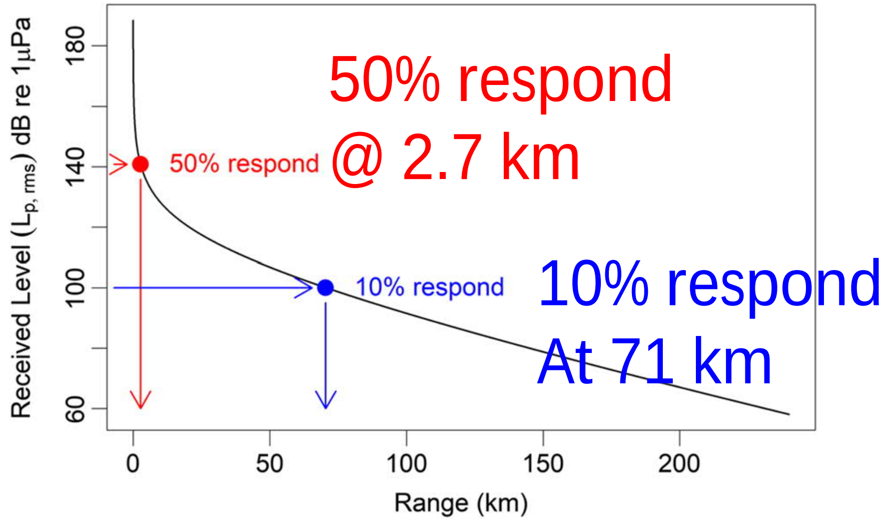
- Standard method: set threshold at received sound level where probability of response is 0.5 – the RL_{p50}
- Example:

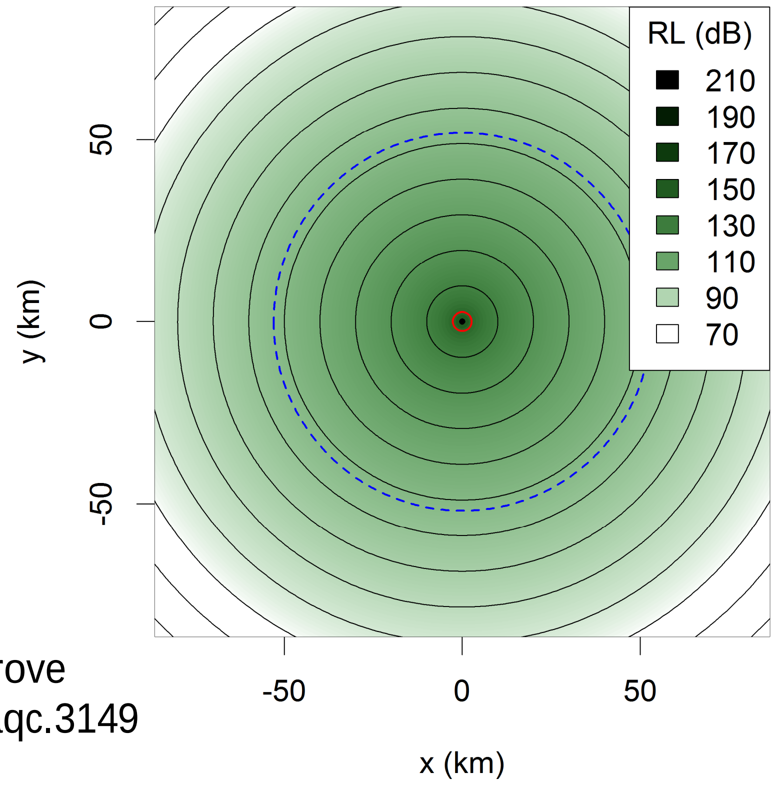
(dose:response function from Miller et al. (2014 JASA 135:975)



Translate received level into range

- Assume source level and propagation model





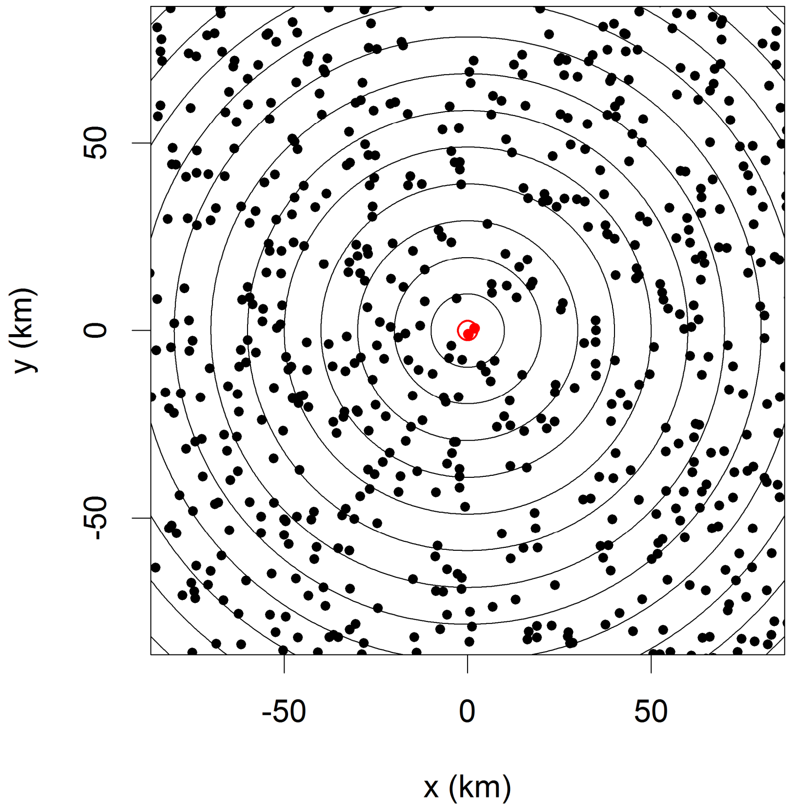
Tyack PL, Thomas L (2019) Using dose–response functions to improve calculations of the impact of anthropogenic noise. DOI: 10.1002/aqc.3149

Translate range into expected number of animals affected assuming step function

- Assume uniform animal density 1/km^2
- For step function assume all animals within the 2.7 km 50% threshold radius will respond - half are within and half are outside

Predicted takes =

$\pi \times 2.72 =$ 23

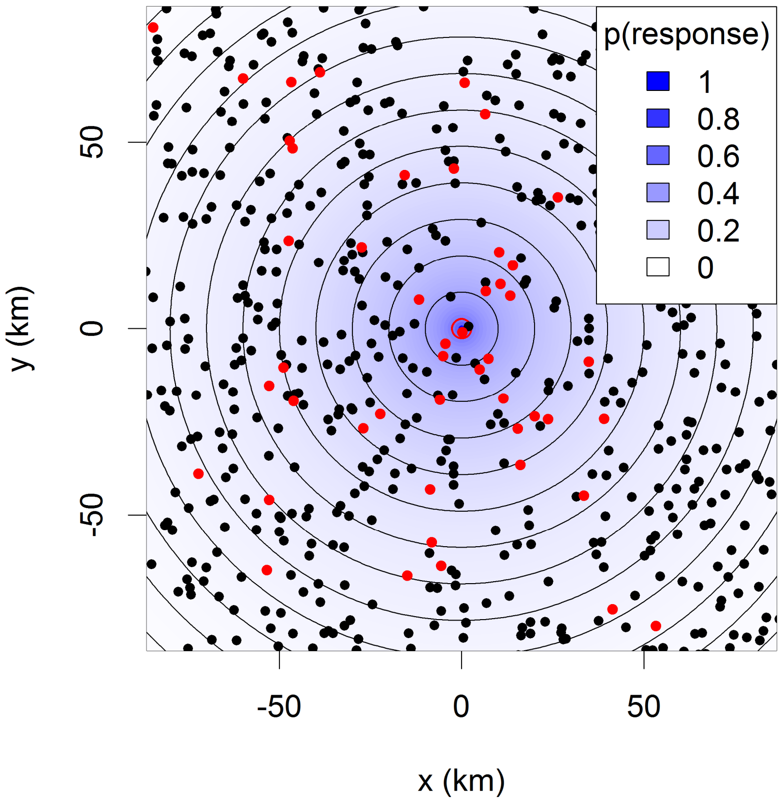


Translate range into expected 10% of whales are affected out to 71 km

- Assume uniform animal density 1/km^2
- Assume 10% of animals within the 71 km threshold radius will respond

Predicted takes =

$0.1 \times \pi \times 71^2 =$ **1584**



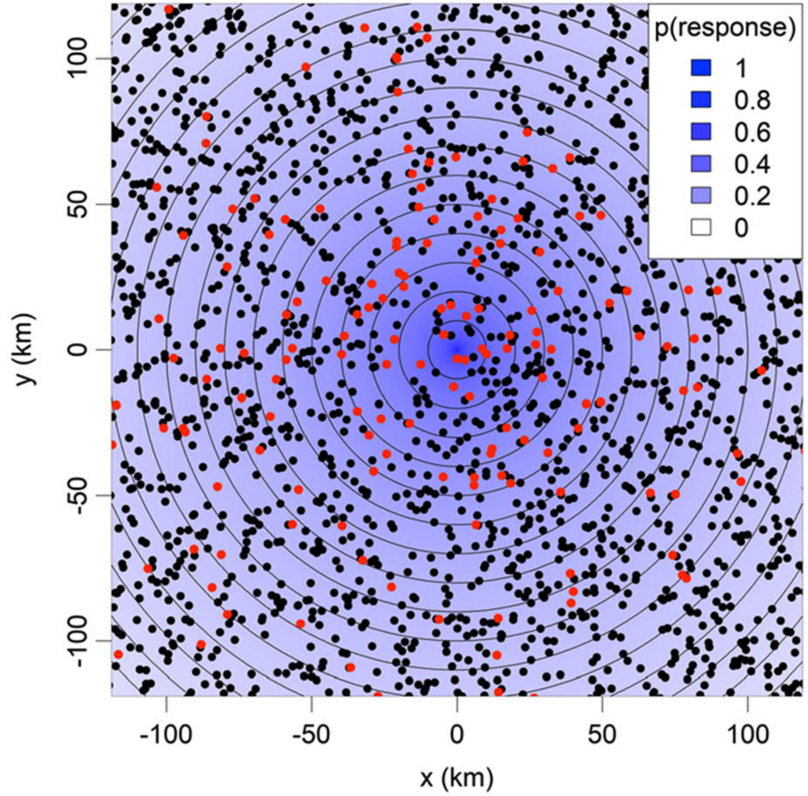
Step function underestimates number of animals affected compared to continuous function

Prediction from continuous dose-response function:

"Correct" predicted

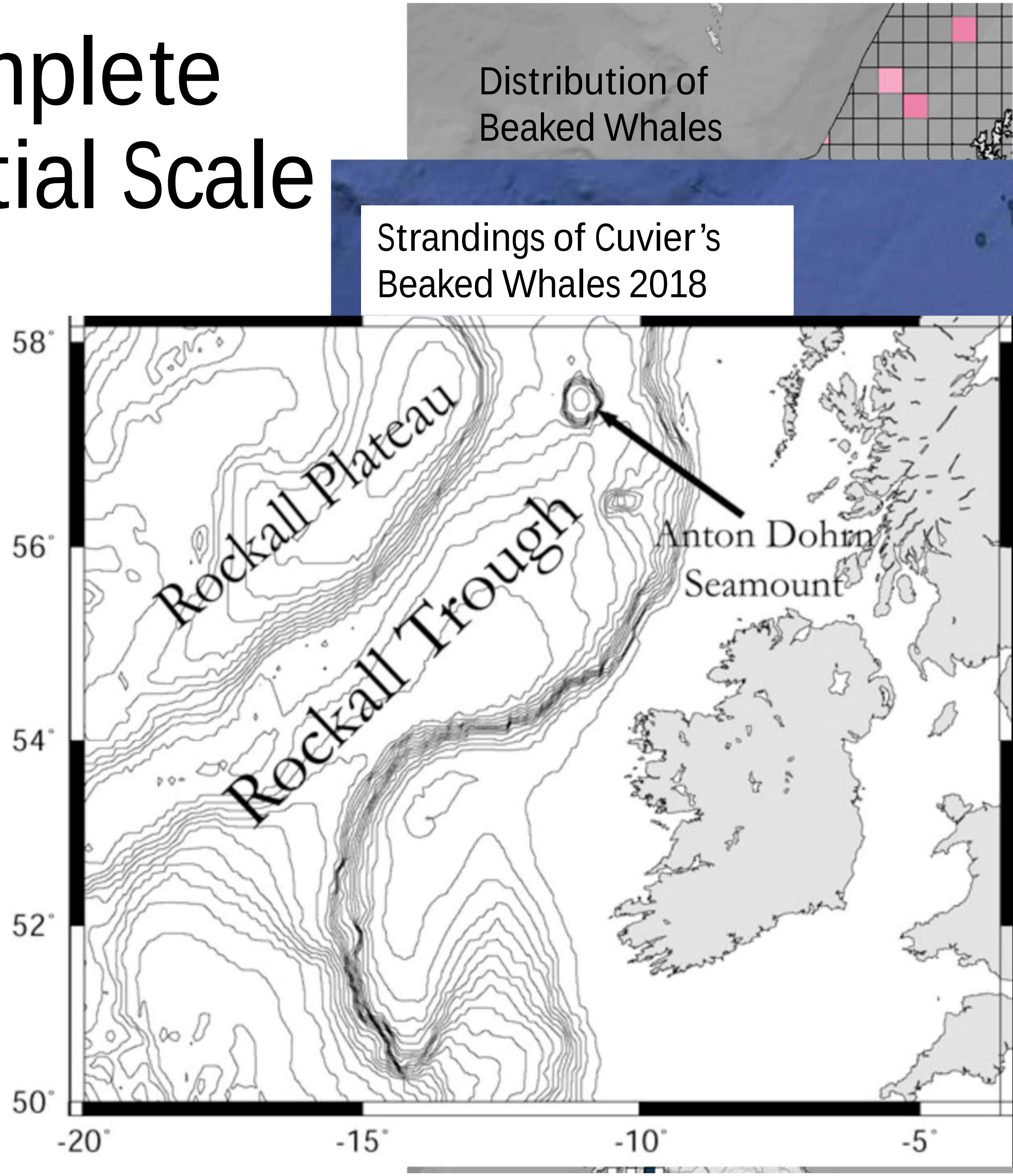
\# of takes = 6437

- Why so many more?
  - There are many animals at larger ranges
  - Even though p(response) is low, it is not zero, so some respond



Noise Register Must Be Complete And Cover Appropriate Spatial Scale

- Marine Scotland Interactive maps the distribution of species and stresssors
- But all sounds need to be logged
- >100 beaked whales stranded dead on Scottish, Irish, and Icelandic beaches in summer 2018
- Likely <10% of whales would drift ashore so possibly ~2000+ animals killed in deep Rockall Trough habitat
- Effects are consistent with naval sonar
- But sonar usage is not reliably coded in the impulse sound register and spatial coverage may not be sufficient

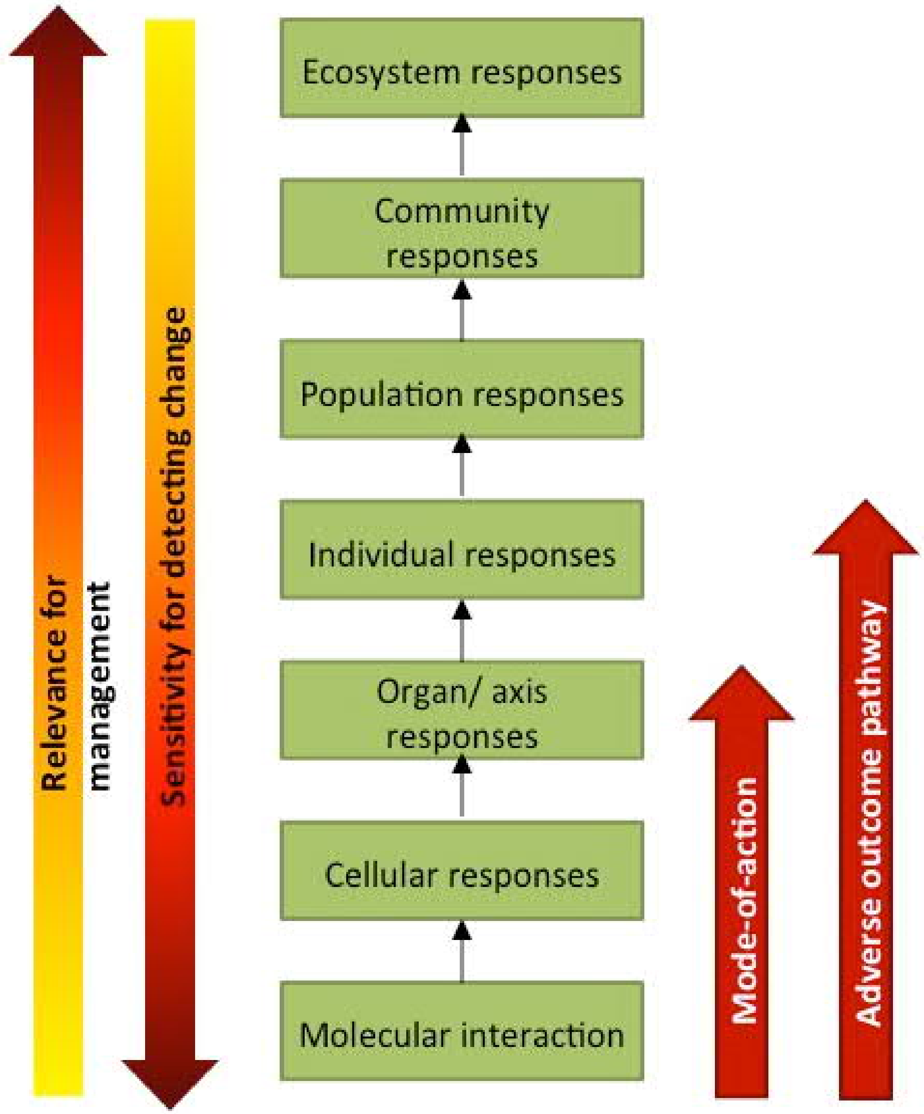


MSFD Impulse Noise Register

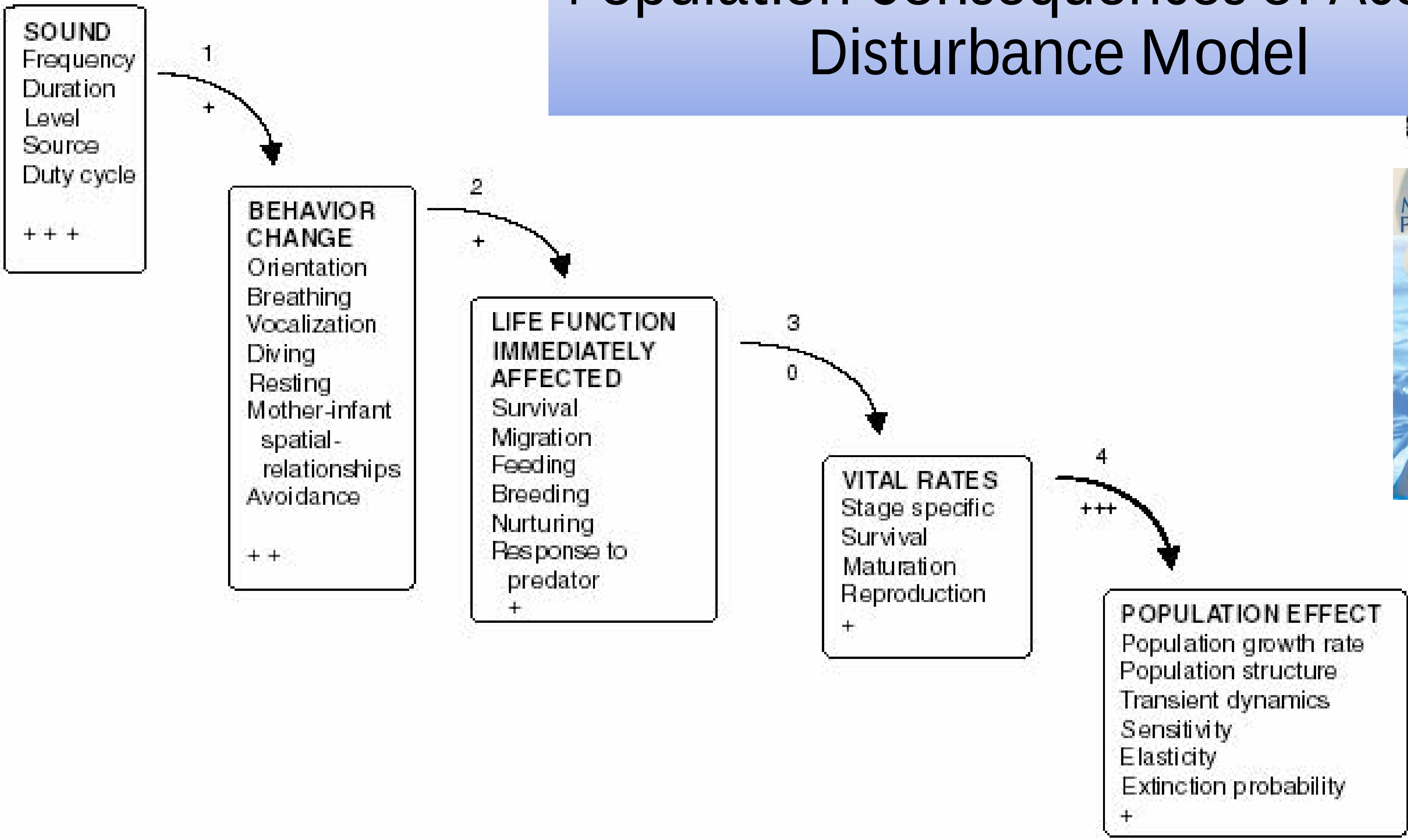
- A joint register of the occurrence of impulsive sounds should be set up at least on a Regional Sea level
- Most important sound-sources for inclusion in the register: Airguns, pile-driving, explosives, sonar working at relevant frequencies and some acoustic deterrent devices
- Information on all sources should be included [see Van der Graaf et al., 2012]. TSG Noise therefore suggest that data on explosives and military activities should also be included in the register
- Need to develop a system that meets needs for national and NATO security classification and commercial secrets AND guarantees complete register

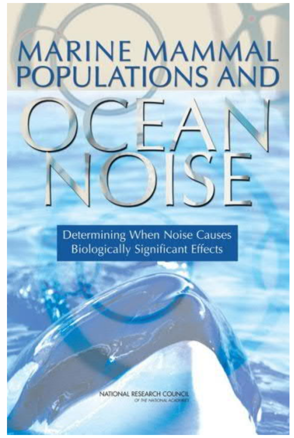
Dekeling, R.P.A., et al. 2014. Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications, JRC Scientific and Policy Report EUR 26555 EN, Publications Office of the EU, Luxembourg, doi: 10.2788/27158

High Priority Basic Science Question: Longer term cumulative effects of multiple stressors on populations

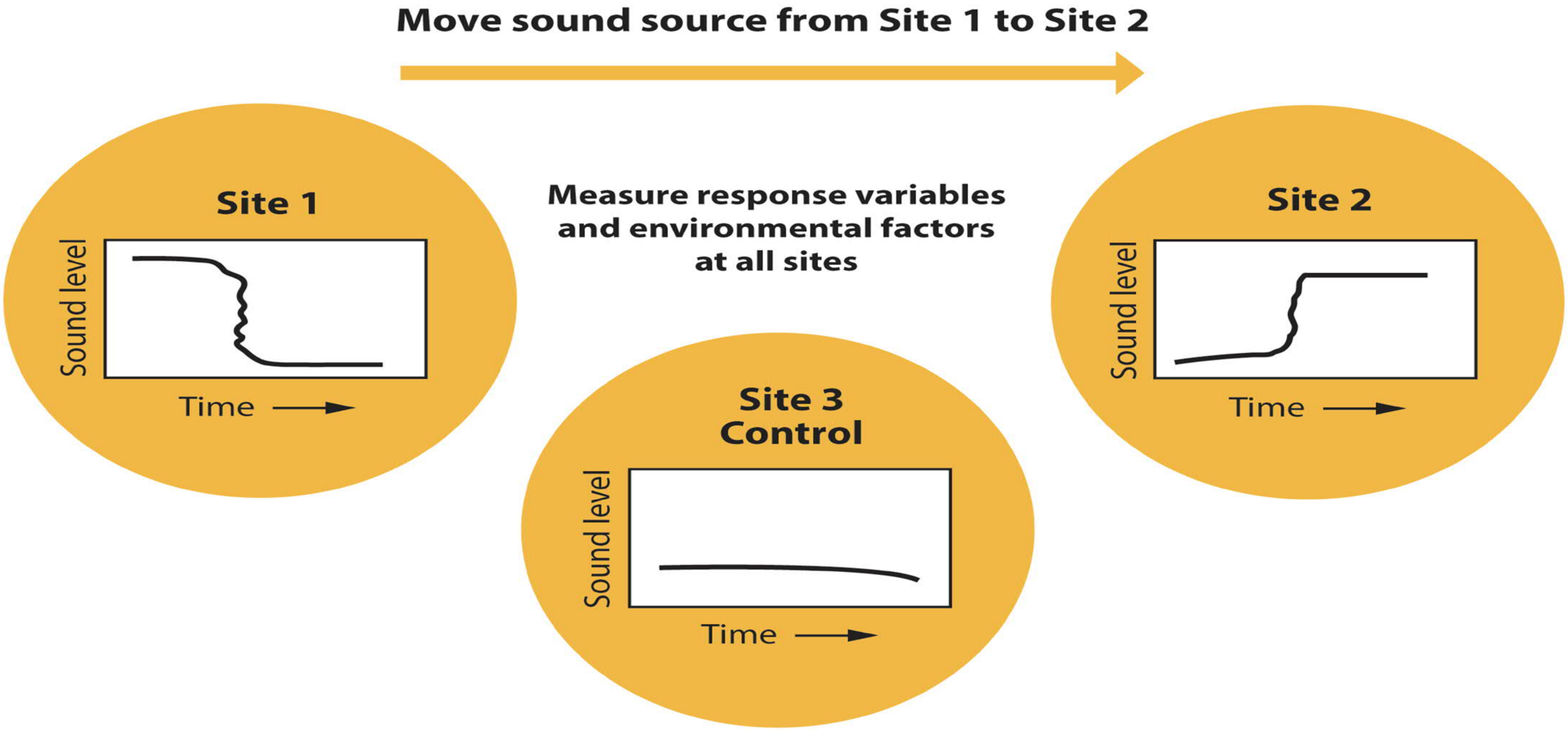


Population Consequences of Acoustic Disturbance Model





Before/After/Control Experimental Design

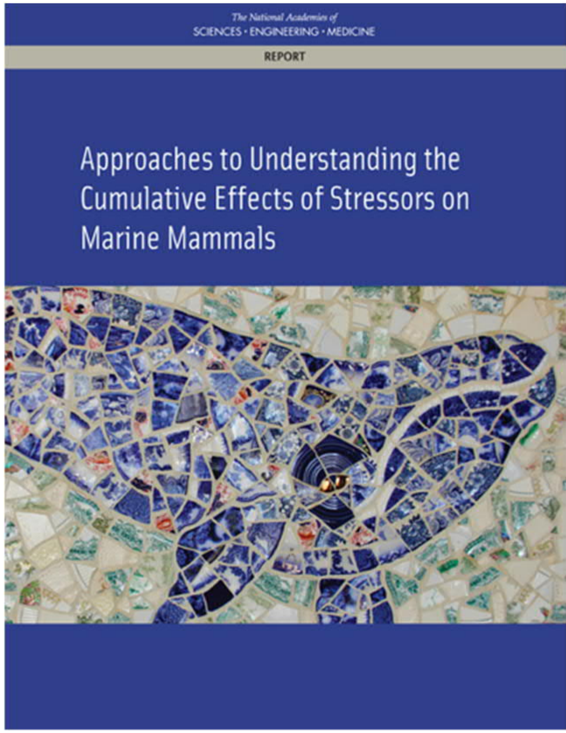


International Quiet Ocean Experiment Science Plan
(2015) ISBN: 978-0-692-43167-2

NATIONAL ACADEMIES (2017) REPORT on Cumulative Effects of Anthropogenic Stressors on Marine Mammals

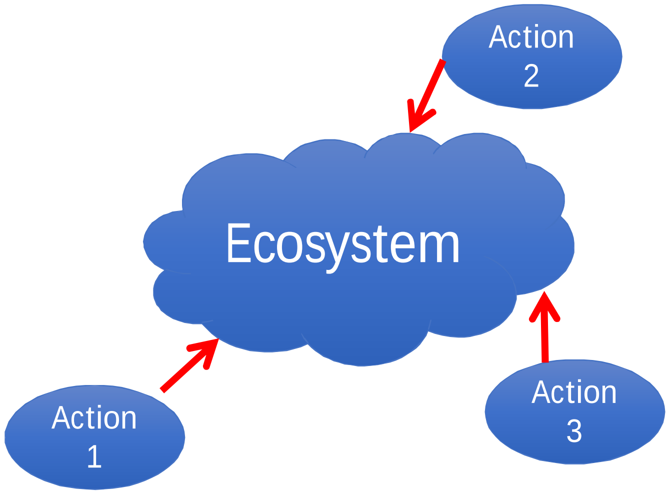
RECOMMENDATIONS

- Agencies charged with monitoring and managing the effects of human activities on marine mammals should identify baselines and document exposures to stressors for high priority populations.
- Uncertainties about animal densities, sound propagation, and effects should be translated into uncertainty on take estimates, for example through stochastic simulation.

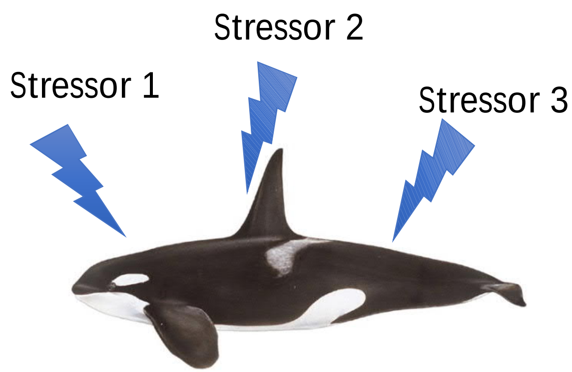


Contrasting regulatory vs biological definitions of cumulative effects

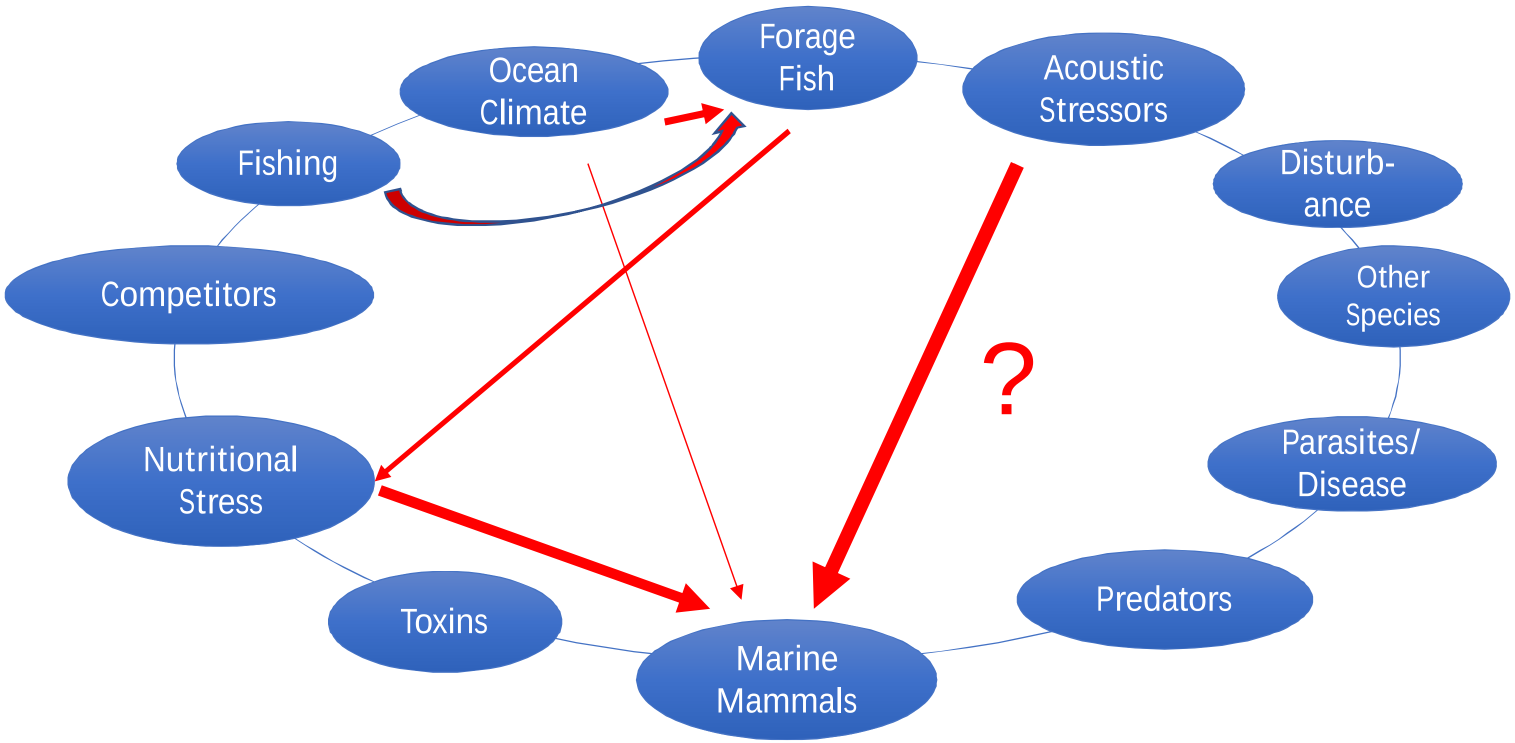
Cumulative effects are defined by policy makers as the incremental impact of a proposed action when added to the other past, present and reasonably foreseeable actions.



Biologists focus on the individual animal or population, with effects accumulating when animals are repeatedly exposed to the same or different stressors.



Indirect Effects Visualized with an Ecological Interaction Web



What stressors can practically be reduced to maintain good environmental status?

- The science of cumulative effects has low predictive power compared to regulatory demands to assess these effects.
- The most important goals for managing cumulative effects are (1) identifying when the cumulative effects of stressors risk transitioning a population or ecosystem to an adverse state; and (2) identifying practical reductions in stressors to reduce this risk

Possible to Change Rapidly

- Noise Pollution
- Fishing Effort
- Shipping

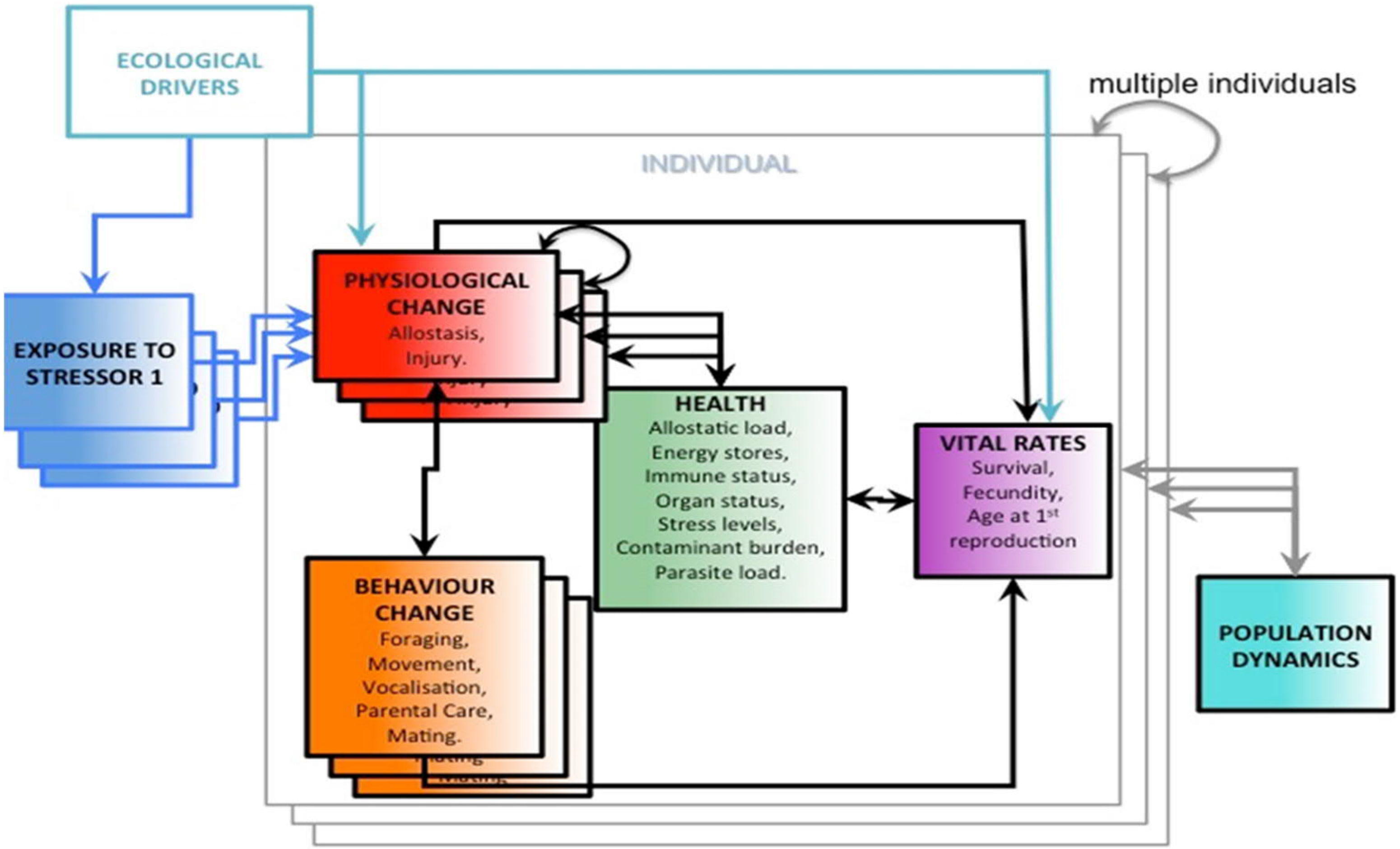
Slow to Change Effects

- Chemical pollution

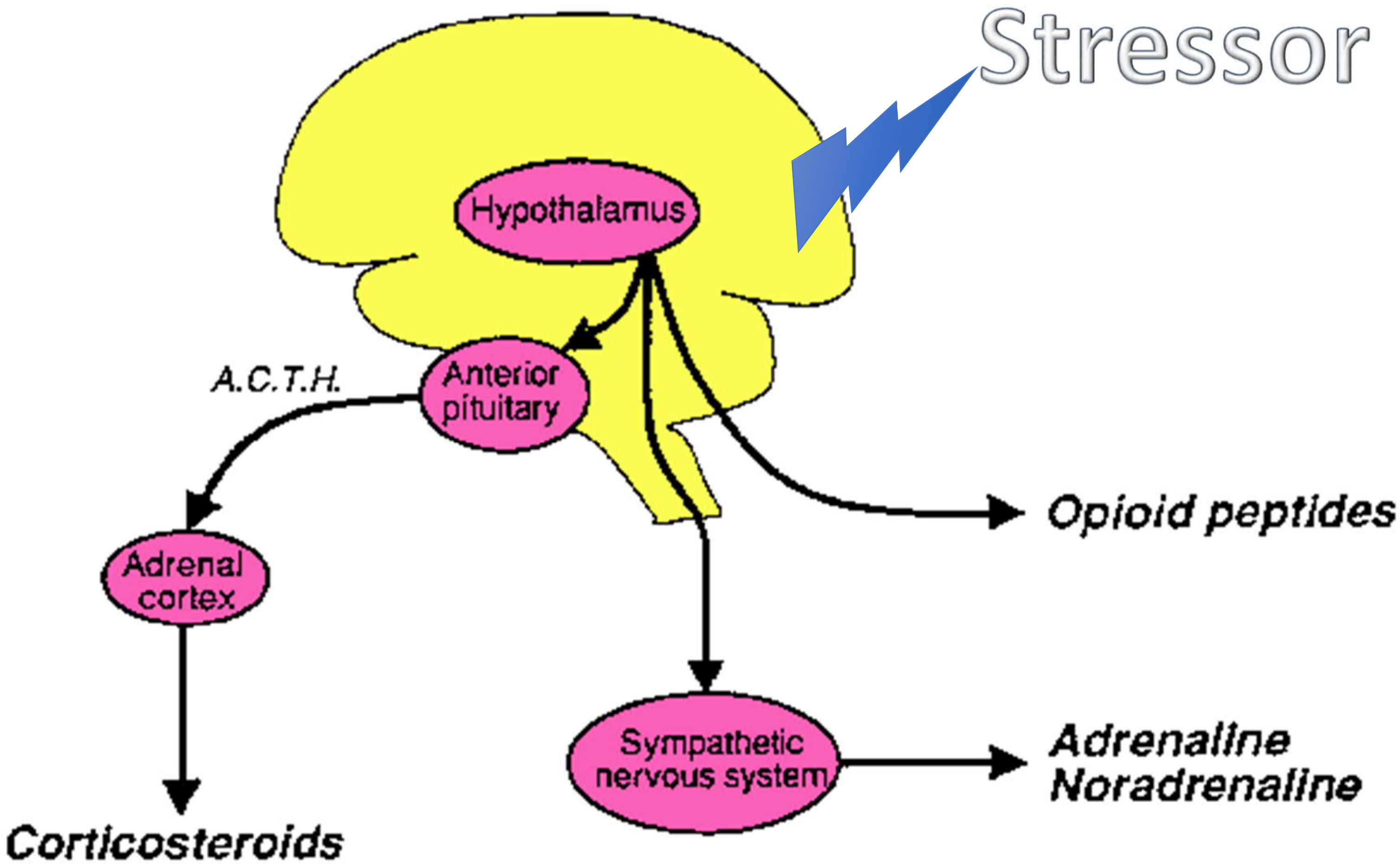
Difficult to Change

- Climate change
- Natural Stressors (except by indirect effects)

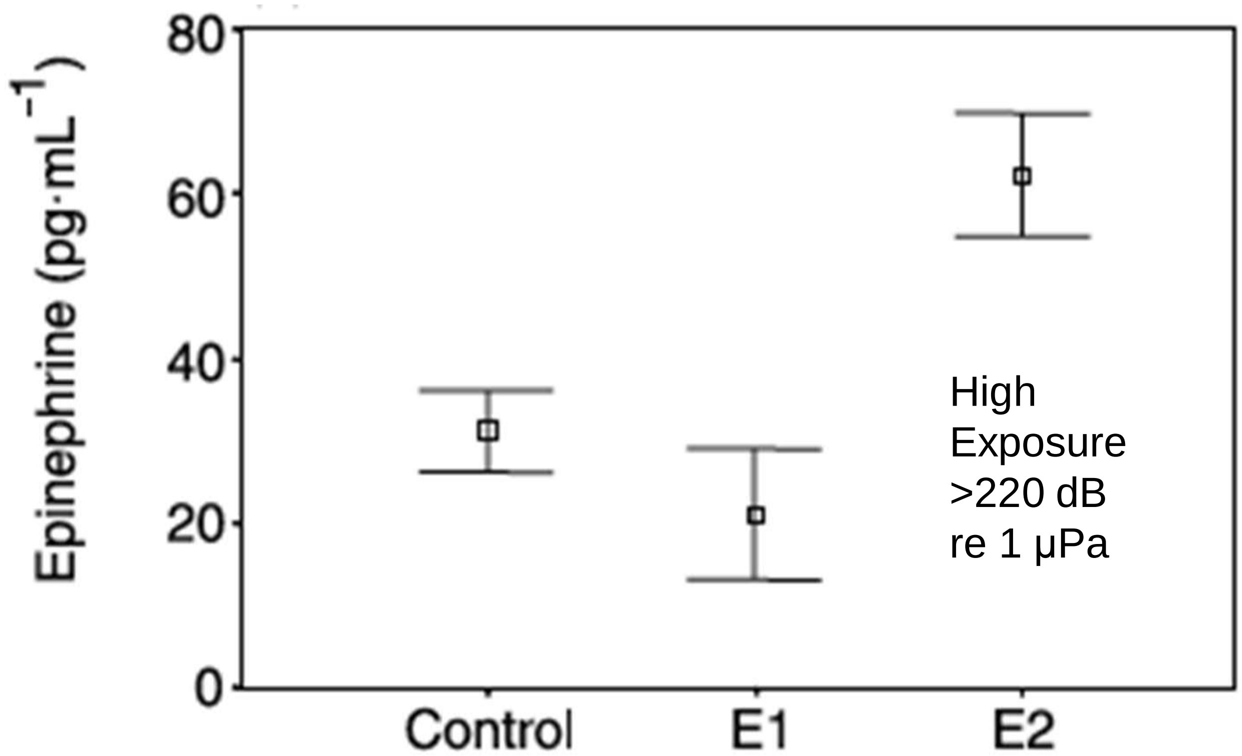
Modelling Population Consequences of Multiple Stressors



Neuroendocrine Response to Stressor

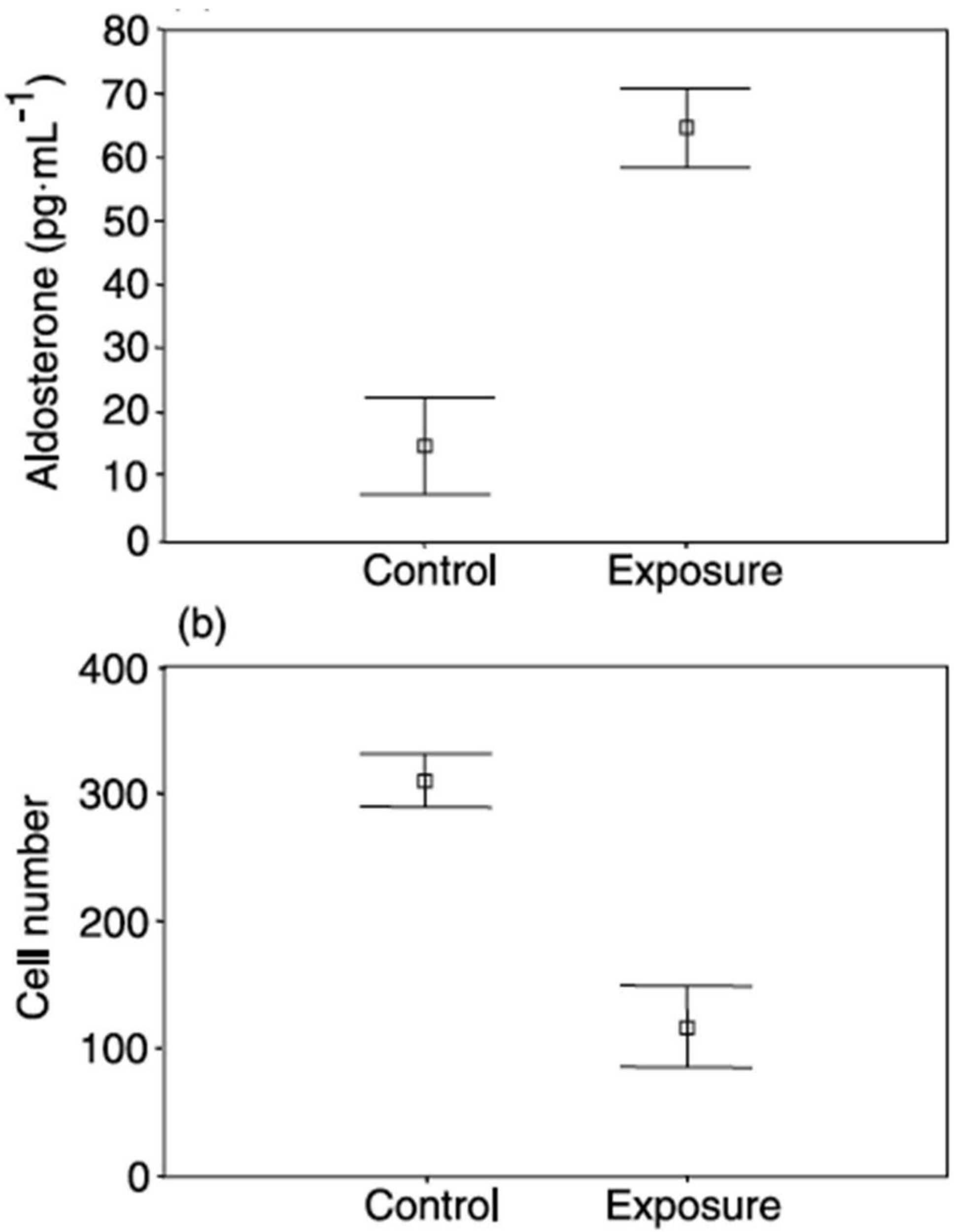


Increased Epinephrine in Captive Beluga Exposed to Intense Impulse Sound

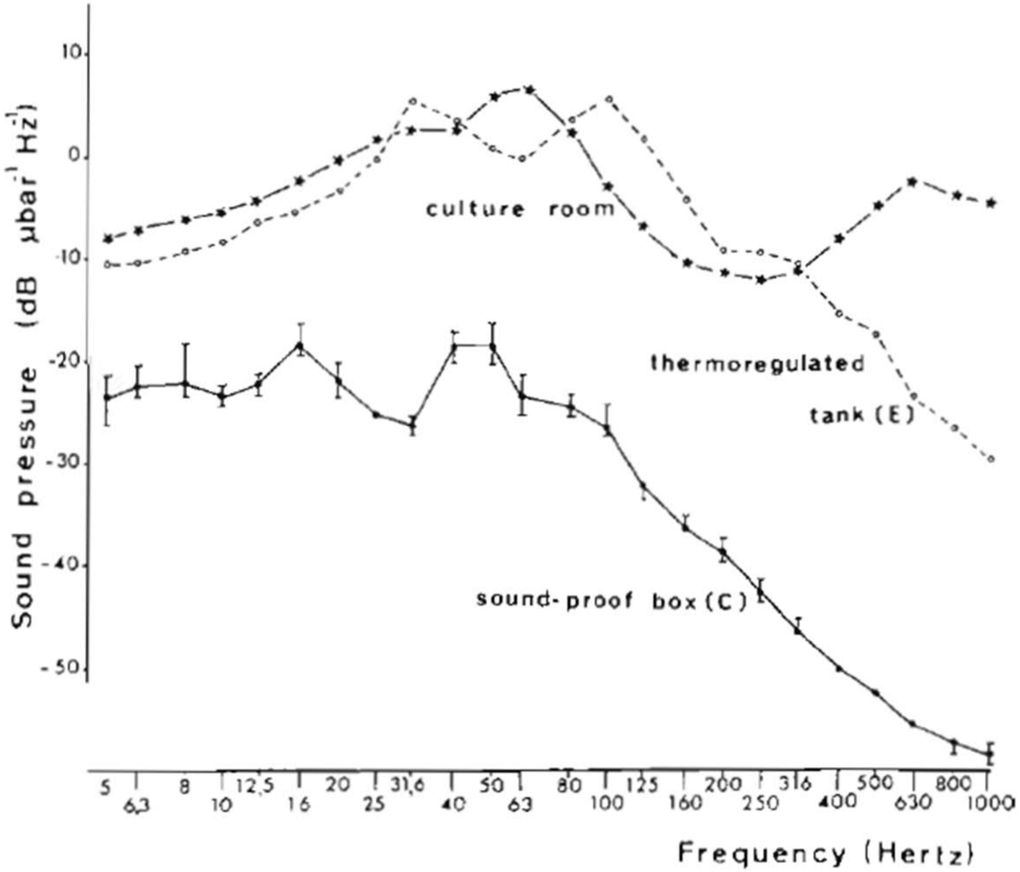


Romano et al. 2004 Can. J. Fish. Aquat. Sci. 61: 1124–1134

Stress Response Increases and Immune Response Decreases with Exposure to Intense Sound

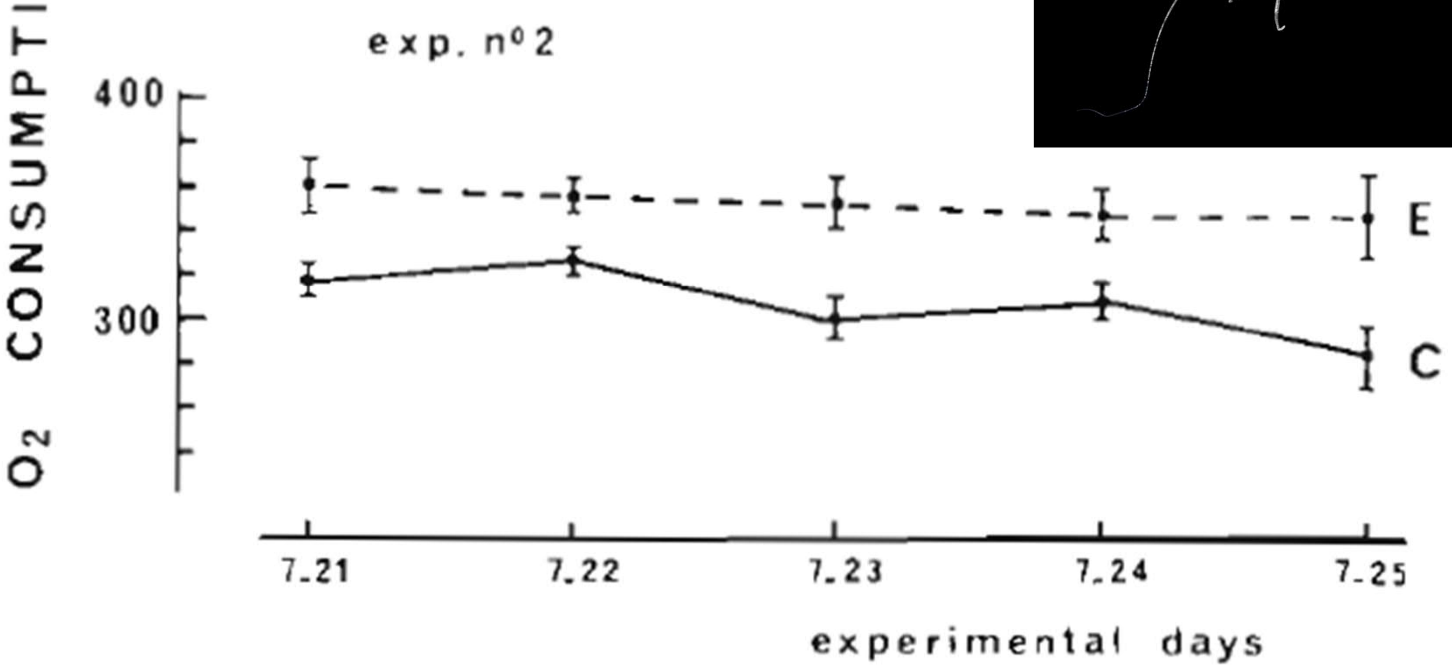


Normal Aquaria are Loud



Regnault and Lagardere 1983 Mar Ecol Prog Ser 11:71-78

Shrimp (*Crangon crangon*) Have Higher Metabolic Rate in Noisy Aquaria



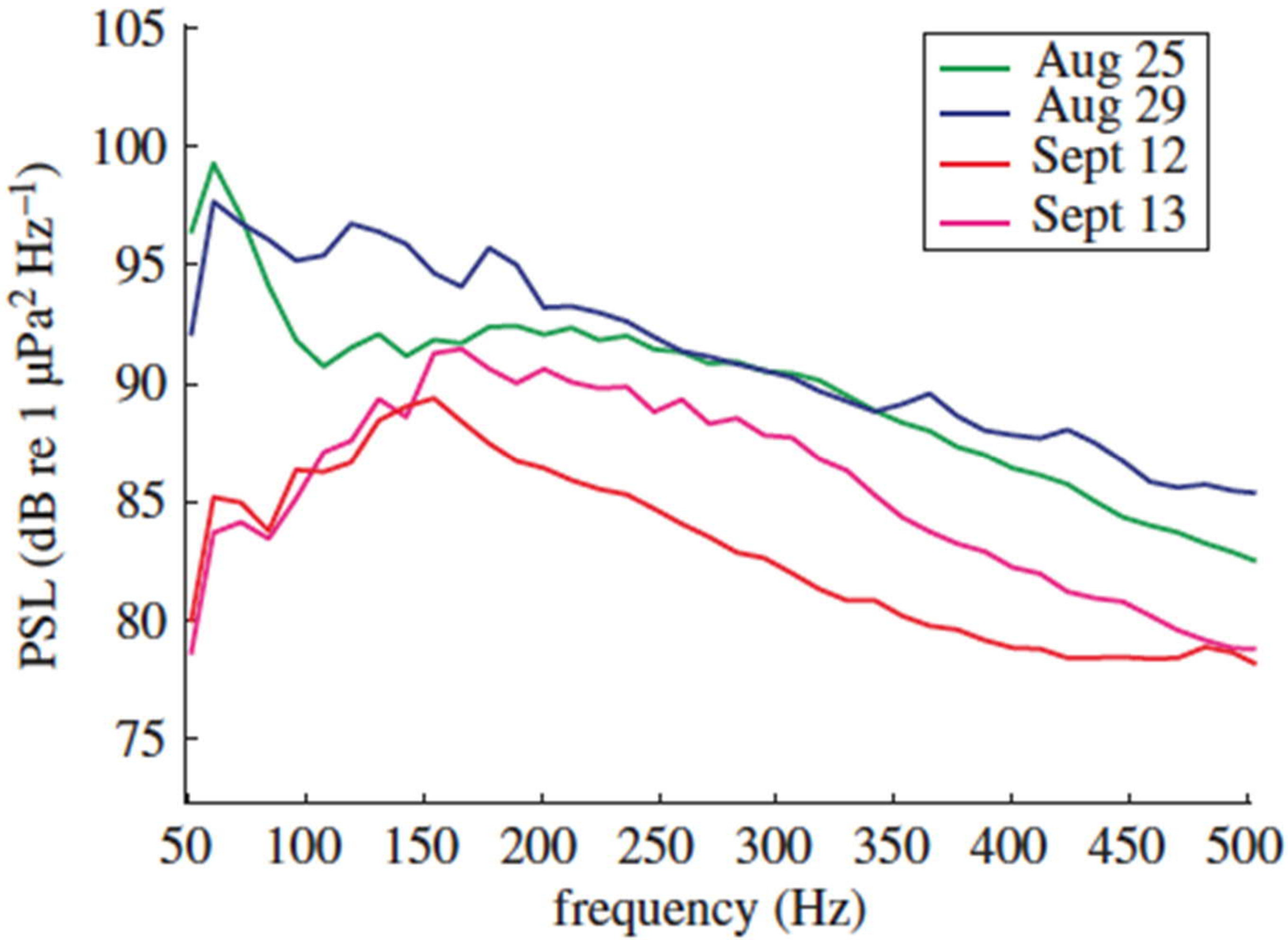
Regnault and Lagardere 1983 Mar Ecol Prog Ser 11:71-78

Long term effects of Noise Mediated by Metabolic Changes

- 30 dB increase in Noise →
- 15% increase in Metabolism
- Over 3 months, this increase in metabolism leads to significant reduction in growth and reproduction

Lagardere J-P 1982 Mar Biol 71:177-185

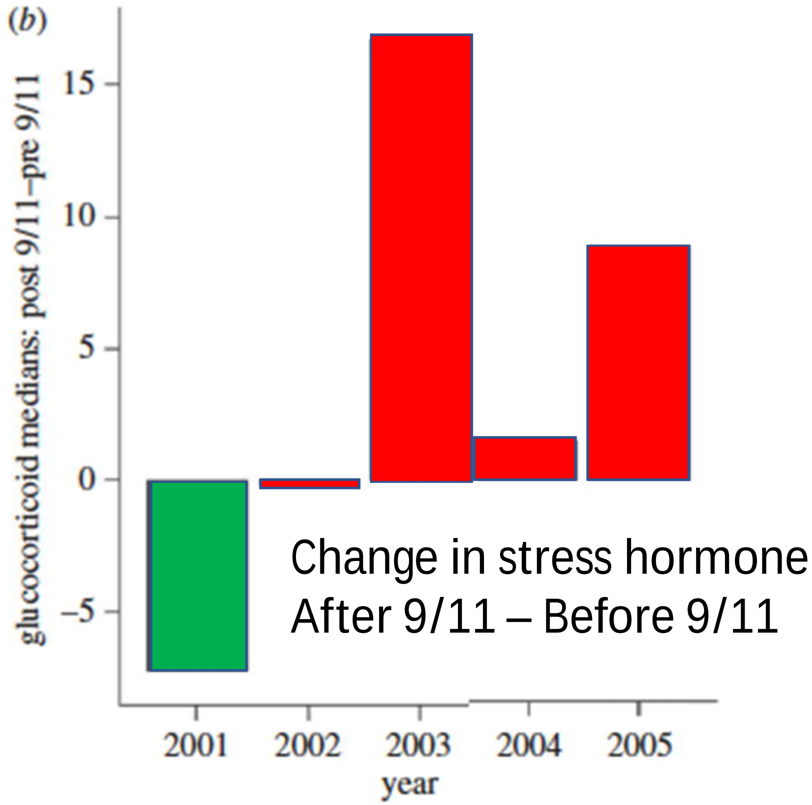
Shipping Noise Drops After 9/11



Rolland et al. 2012 Proc Roy Soc B 10.1098/rspb2011.2429

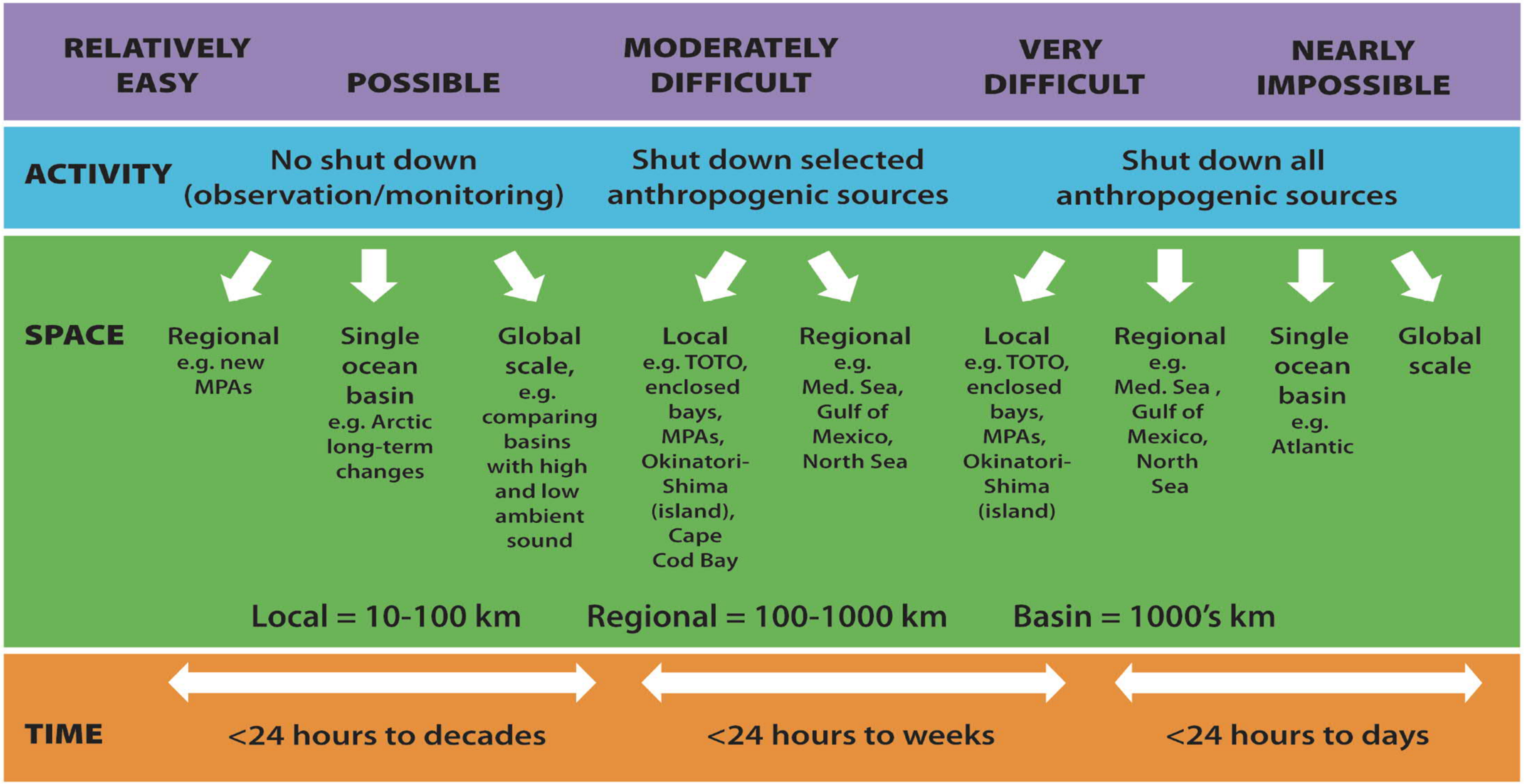
Quasi-Experiments

Stress Hormones in Right Whale Feces Dropped After 9/11 in 2001 but not Later Years



Rolland et al. (2012) Proc Roy Soc Ship Noise and Stress in Whales

How Difficult To Shut Down Sources to Establish Baseline?



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(2015) ISBN: 978-0-692-43167-2

What does all this mean for JOMOPANS

- What physical quantity to measure? Pressure. Particle Velocity?
- Logic for temporal sampling
- Logic for frequency sampling
- Logic for sampling space
- Partition ocean sound budget into natural vs anthropogenic OR use dose-response function to estimate effects?
- Validation

JOMOPANS Specifies Acoustic Metrics

in 4 dimensions: physical quantity, time, frequency, and space.

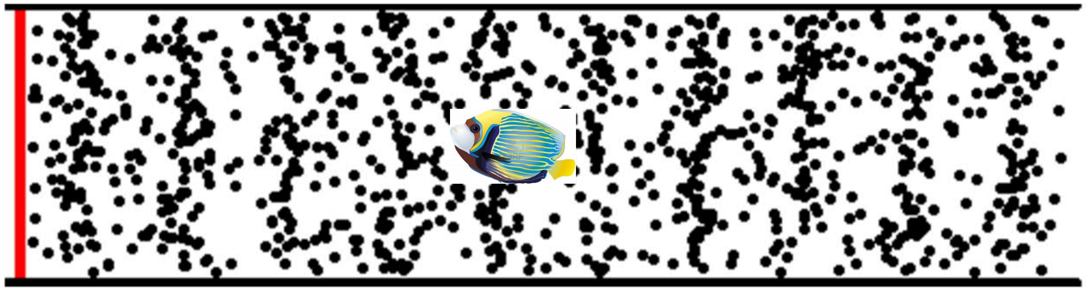
- **Physical quantity**: sound pressure level (SPL), measured in decibels relative to 1 micropascal (dB re 1 μPa).
- **Temporal unit**: percentiles of the SPL distribution, based on individual SPL measurements of 1 second (snapshot duration). The period over which the percentiles will be computed is one month. Suggested percentiles are 5th, 10th, 25th, 50th, 75th, 90th, and 95th.
- **Frequency**: one-third octave bands, with centre frequencies between 10 Hz and 20 kHz, defined using the base-ten convention (ANSI 2009; IEC 2014).
- **Space**: Depth-averaged value of the metric either at the centroid of each grid cell, or as a spatial average of the levels within the grid cell. Geospatial grid referenced using the standardised C-square notation (Rees 2003).

Merchant, N. D., Farcas, A., Powell, C. F. (2018) Acoustic metric specification. Report of the EU INTERREG Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS).

Need to Measure Particle Velocity & Pressure?

- Most acoustically-sensitive marine organisms primarily sense particle motion (fish and acoustically sensitive marine invertebrates),
- Sound pressure is proportional to particle motion in areas far from the sound source and away from boundaries (sea surface and seabed), and sound pressure may arguably be a suitable proxy for particle motion at the large scales considered in regional monitoring programmes such as JOMOPANS.
- NOT correct for benthic animals. Relevant scale is the scale at which the receiver senses the sound. Test particle velocity measured at surface and bottom vs predicted from pressure.

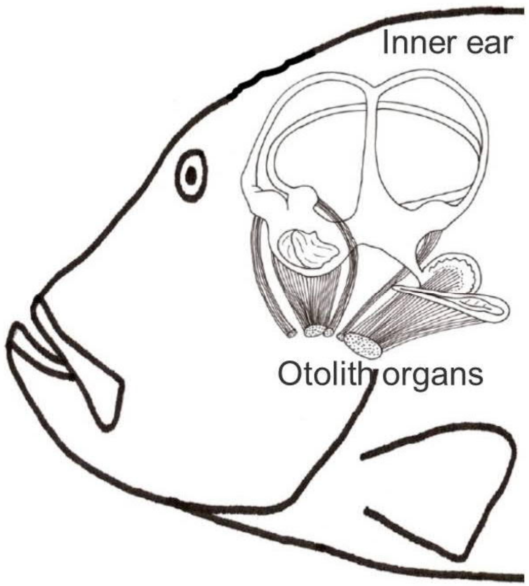
How marine animals hear

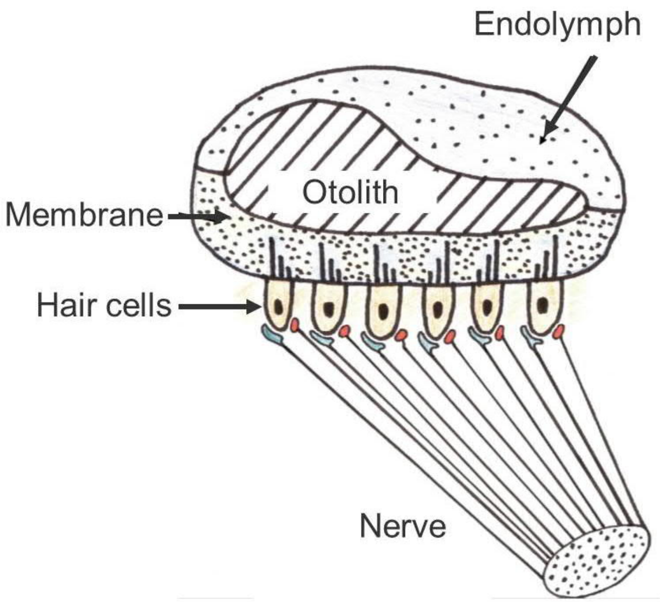


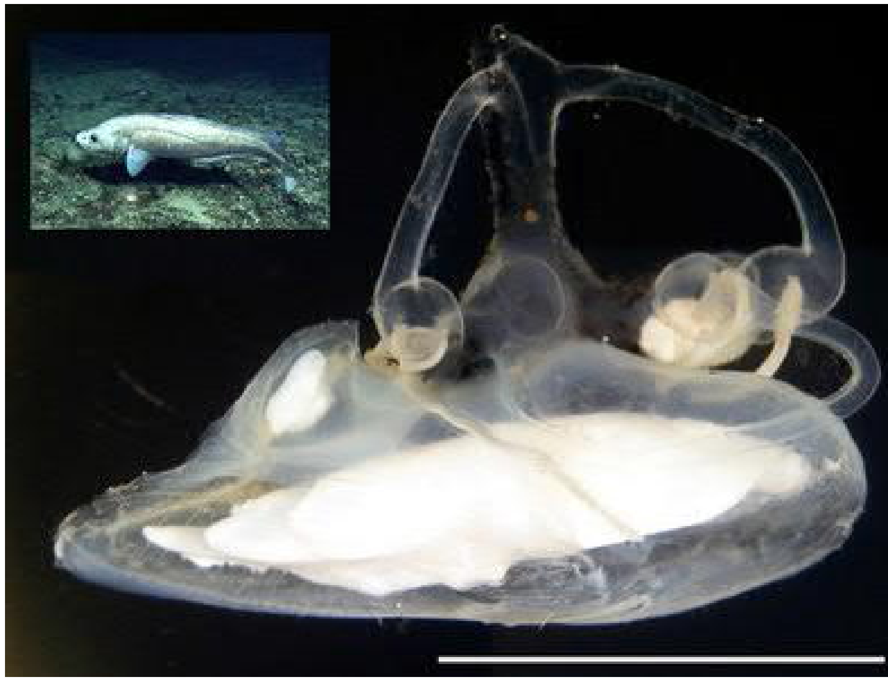
- Birds and Mammal ears detect the pressure generated by the acoustic signal
- But most fish and invertebrates like squid detect the particle displacement generated by the acoustic signal
- Sounds low enough in frequency that the particle displacement can move the whole animal back and forth

Fish and Invertebrate Hearing

As the animal moves back and forth under the influence of the particle displacement, a dense mass called an otolith in fish and a statocyst in invertebrates moves less. Sensory cells called hair cells sense the inertial force between the whole animal and the mass.







JOMOPANS decided not to measure particle motion but acknowledges the problem

Methods in Ecology and Evolution

British Ecological Society

Methods in Ecology and Evolution 2016, **7**, 836–842 doi: 10.1111/2041-210X.12544

Particle motion: the missing link in underwater acoustic ecology

Sophie L. Nedelec[1]*, James Campbell[2], Andrew N. Radford[1], Stephen D. Simpson[3] and Nathan D. Merchant[4]

Need for Improvements in Measurement Systems for Particle Motion

Animals in substrate?

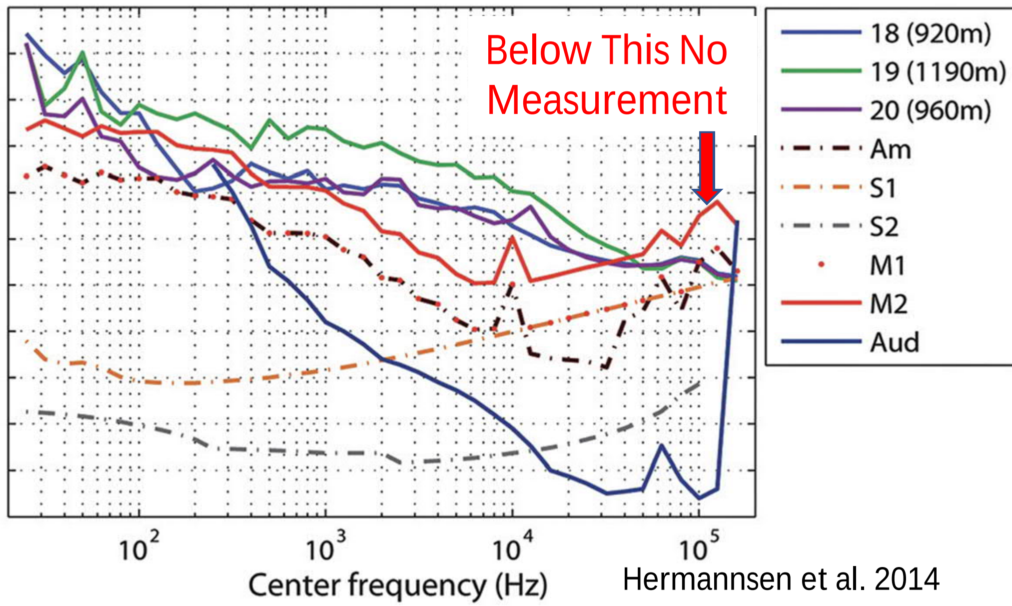
Sampling duration

- MSFD call for annual average makes no sense from animal bioacoustics perspective
- JOMOPANS uses logic and good science to come up with a reasonable compromise
  - Integration time of hearing is ~0.1 s
  - But difficult to estimate energy at low freq with such a short time sample
  - Empirical analysis shows 1s gives similar result
- Conclusion: snapshot duration of 1 second.

Frequency

- ~~MSFD calls for measuring annual averages at 2 1/3 octave bands centred at 63 and 125 Hz~~
- JOMOPANS: monitor within the 1/3 octave bands centred between 10 Hz and 20 kHz. The frequency range required to encompass to lower and upper bounds of these bands is 8.91 Hz to 22.44 kHz.

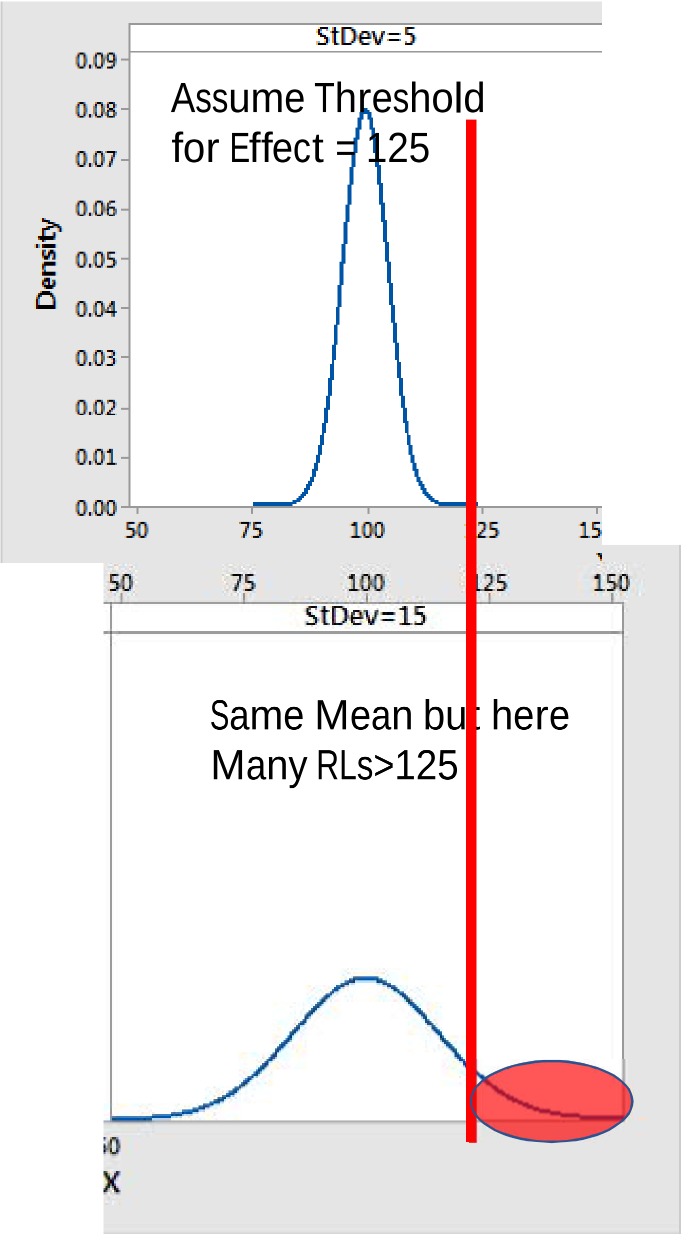
Species/group	63/125 Hz appropriate proxy?
Fish and invertebrates	Yes,
Minke	Possibly,
Seals	Unlikely
Harbour porpoise	Unlikely
Various dolphin	Unlikely



Hermannsen et al. 2014

Space

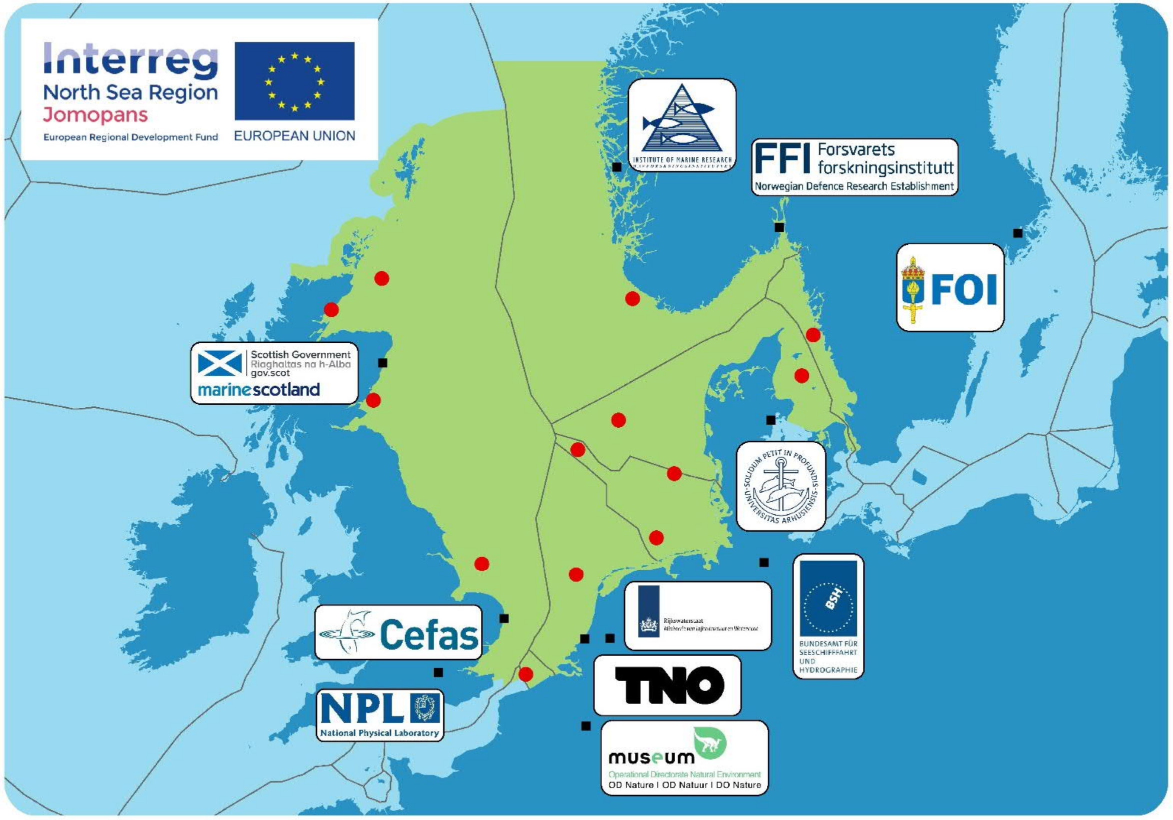
- Conclusion: indicator maps represent the depth-averaged value of either the centroid of each grid cell, or the spatially averaged value of the metric for each grid cell.
- Agree strongly re relevance of depth
- Disagree with limiting to average value across space
- Need to give distribution of values just as for time stats
- Aren't the problems with averaging that are discussed for time equally relevant for space?



Improve coverage of central North Sea?

Acoustic monitoring to validate noise map and impulse register?

- Compare number of impulses detected against register.
- If more are detected than registered, there is a problem
- If not, use modeling to estimate Prob(detection)
- Use moving platforms to cover critical areas



Partition sound to anthropogenic vs natural?

- The total distribution of underwater sound levels is composed of natural and anthropogenic sounds.
- The objective of monitoring is not to measure the total distribution of sound levels, but to measure levels of anthropogenic noise pollution.
- To understand the potential impact of underwater noise pollution, it also necessary to understand the extent to which noise pollution exceeds natural levels.
- However, in practice, only the total distribution of sound levels can be measured.

NO – I TAKE DOSE-RESPONSE APPROACH. WHAT YOU NEED TO DO IS COMPARE TOTAL SOUND TO THRESHOLD FOR EFFECT

Merchant, N. D., Farcas, A., Powell, C. F. (2018) Acoustic metric specification. Report of the EU INTERREG Joint Monitoring Programme for Ambient Noise North Sea (JOMOPANS).

Knowledge Gaps

- MFSD TG Noise (2012) most relevant issue: Better understanding of the impacts of noise on biota, in order to help MS to better specify GES.

I would specify

- Use Full Dose-Response Function to Ensure Appropriate Spatial Scales
- Make sure monitoring captures enough information to predict different effects
  - SPLrms, SPLpeak, SELcum, Weighting Functions, Runs of Effective Quiet
- Validation of maps of stressors, animals, and estimated effects
- Measurement of particle velocity

Van der Graaf AJ, et al. (2012). European Marine Strategy Framework Directive - Good Environmental Status (MSFD GES): Report of the Technical Subgroup on Underwater noise and other forms of energy.