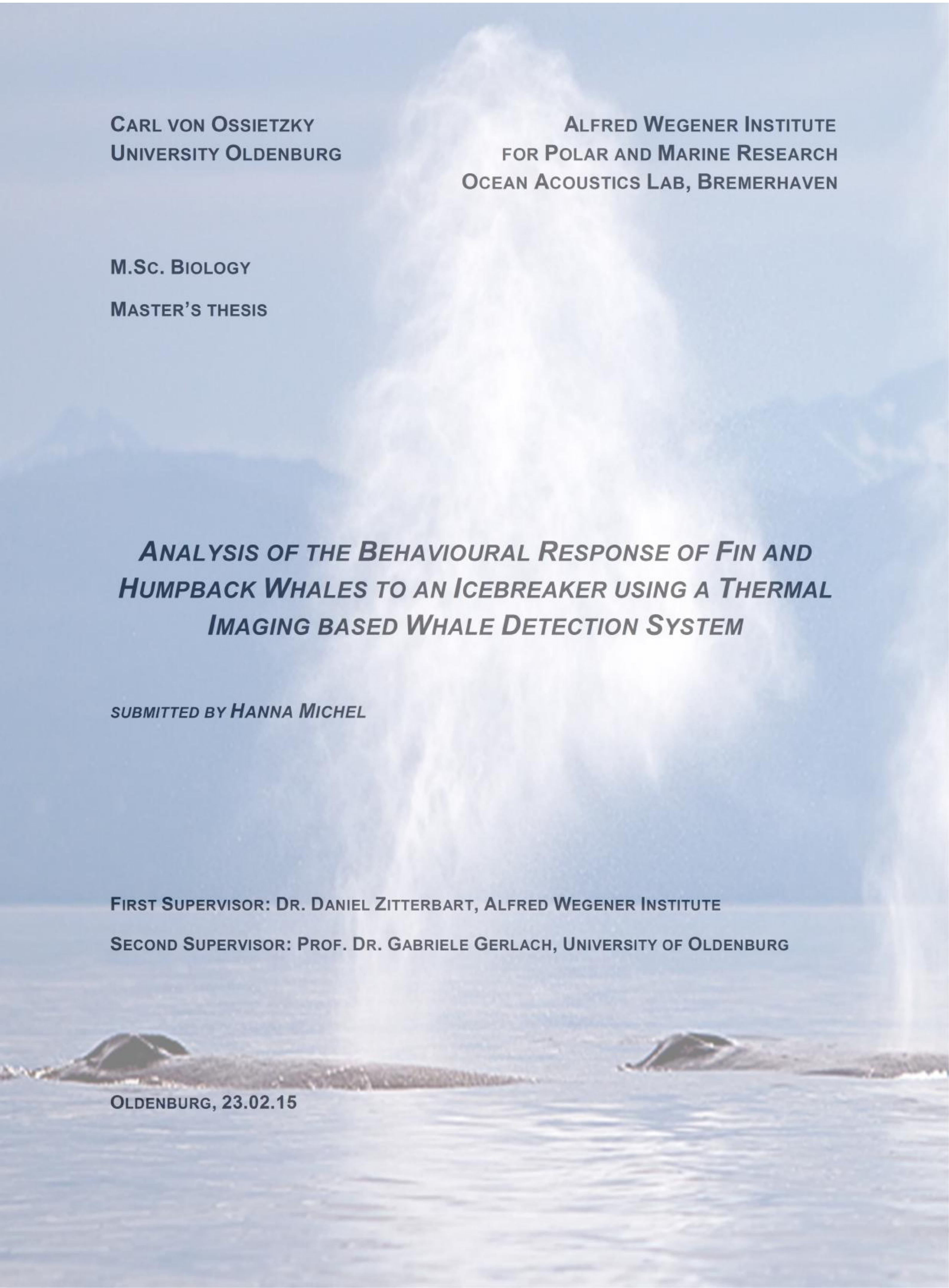

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M.SC. BIOLOGY

MASTER'S THESIS

ANALYSIS OF THE BEHAVIOURAL RESPONSE OF FIN AND HUMPBACK WHALES TO AN ICEBREAKER USING A THERMAL IMAGING BASED WHALE DETECTION SYSTEM

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Summary

Cetaceans have evolved a sophisticated auditory sense and rely on sound as principal mean for underwater communication and sensing. Hence, they are affected by noise that is introduced in the world's oceans by various human activities, and disturbance of marine mammals by anthropogenic noise is of great concern. However, over 30 years after the first studies of the effect of noise on marine mammals, its mechanism is still not understood. Documented effects range from short-term behavioural changes to injury and death, while other studies have shown no effect at all.

In this thesis, a ship-based thermal imaging based whale detection system was used for retrospective analysis of the behavioural response of fin and humpback whales to the German research icebreaker *Polarstern* in the Southern Atlantic Ocean. A total of 17 encounters was analysed; during five of these encounters a behavioural response of the whales was observed. As the vessel approached the whales and came closer, the whales changed their swimming direction from swimming virtually parallel to *Polarstern* to swimming perpendicularly or in the opposite direction of the ship's heading. Thereby, the distance between the pods and the ship was increased quickly. The direction change ranged from 43-97°. The five pods showing behavioural responses were observed at minimum distances of up to ~1500 m from *Polarstern*. Three pods detected in the same range and nine pods observed at greater distances did not show a behavioural change. Therefore, proximity to the ship and, thus, the sound pressure level that the whales received likely played an important role since sound pressure levels decrease with increasing distance to a sound source. The behavioural responses of the five pods suggest that the whales were avoiding high sound levels generated by *Polarstern*.

Furthermore, the behavioural analysis based on thermal imaging turned out better than analysis based on records of visual observers. More whale blows were detected, the distance estimation was more precise, and the behaviour of whales was recognizable in contrast to data recorded by visual observers.

To this day, the consequences of short-term behavioural changes due to human disturbance on the population-level are unknown. However, a human-caused increase in low-frequency ambient noise must be considered a potential stressor for all baleen whales, and anthropogenic noise has been hypothesized to be involved in the lack of recovery of several cetacean populations. Additional research is needed to understand its biological significance for marine mammals. Further industrialisation of the oceans would be accompanied by increasing noise levels; however, technological advancements could help to lessen the impact of noise from various anthropogenic activities on marine mammals.

Zusammenfassung

Wale und Delphine haben ein hoch entwickeltes Hörsystem und nutzen hauptsächlich Schall zur Kommunikation und zur Wahrnehmung ihrer Umwelt. Daher sind sie von dem Unterwasserlärm betroffen, der durch zahlreiche menschliche Aktivitäten weltweit entsteht, und die Störung von Meeressäugern durch Lärm bereitet große Sorgen. Allerdings ist mehr als 30 Jahre nach den ersten Studien über den Einfluss von Lärm auf Meeressäuger der genaue Wirkmechanismus weiter unbekannt. Dokumentierte Auswirkungen von Lärm reichen von kurzfristigen Verhaltensänderungen bis hin zu Verletzungen und Tod, während andere Studien keinen Einfluss nachweisen konnten.

In dieser Arbeit wurde die Verhaltensreaktion von Finn- und Buckelwalen auf den Deutschen Forschungseisbrecher *Polarstern* anhand von Aufnahmen einer Wärmebildkamera zur Detektion von Walen im Südatlantik analysiert. Während fünf der insgesamt 17 analysierten Begegnungen wurden Verhaltensreaktionen der Tiere beobachtet. Als sich das Schiff nährte und die Distanz verringerte, änderten die Wale ihre Schwimmrichtung von parallel zu *Polarstern* um 43-97° und entfernten sich senkrecht von dem Schiff oder schwammen in die entgegengesetzte Richtung. Der Abstand zu *Polarstern* wurde so schnellstmöglich vergrößert. Die minimale Distanz zwischen *Polarstern* und den Gruppen von Walen, bei denen eine Verhaltensreaktion zu beobachten war, betrug bis zu ~1500 m. Drei weitere Gruppen innerhalb dieses Bereichs und neun Gruppen, die in größerer Entfernung gesichtet wurden, zeigten keine Verhaltensänderung. Die Nähe zum Schiff und davon abhängend der Schalldruckpegel, dem die Tiere ausgesetzt waren, scheinen daher wichtige Faktoren bei der Reaktion der Wale gespielt zu haben. Die Verhaltensreaktionen der fünf Gruppen legen nahe, dass die Tiere versuchten, die hohen Schallpegel, die von Polarstern verursacht wurden, zu vermeiden.

Darüber hinaus stellte sich die Verhaltensanalyse basierend auf Aufnahmen der Wärmebildkamera als besser im Vergleich zu visuellen Beobachtern heraus. Mehr Walblase wurden entdeckt, die Distanzschätzung war genauer, und das Verhalten der Tiere war erkennbar, im Gegensatz zu den Daten von visuellen Beobachtern.

Die Konsequenzen kurzfristiger Verhaltensänderungen durch menschliche Störung für eine Population sind bis heute unbekannt. Ein Anstieg von niederfrequentem Unterwasserlärm muss jedoch als potentieller Stressfaktor für alle Bartenwale betrachtet werden und anthropogener Lärm wird für einen von mehreren Faktoren gehalten, der die Erholung gesunkener Wal- und Delphinpopulationen behindert. Weitere Forschungsarbeit ist erforderlich, um dessen biologische Signifikanz für Meeressäuger zu verstehen. Die weitere Industrialisierung der Meere

würde mit weiter steigenden Lärmpegeln einhergehen, allerdings können technologische Fortschiritte dabei helfen, den Einfluss von Lärm von verschiedenen menschlichen Aktivitäten auf Meeressäuger zu vermindern.

Table of Contents

List of Figures

List of Tables

1. Introduction

Due to the physical characteristics of the underwater environment, sound is the most efficient information channel in the ocean (Tyack, 2000). As obligate marine animals, cetaceans have evolved a sophisticated auditory sense and rely on sound as principal mean for underwater communication and sensing (Weilgart, 2007; Wartzok & Ketten, 1999). Hence, they are affected by noise that is introduced in the world's oceans by various anthropogenic activities. As low-frequency specialists, mysticetes or baleen whales might be particularly at risk from noise pollution from still increasing commercial shipping and other low-frequency sounds (Clark et al., 2009).

However, over 50 years after the first studies of the effect of noise on marine mammals, its mechanism is still not understood. Documented effects of noise range from short-term behavioural changes to injury and death, while other studies have shown no effect at all. Effects on behaviour include changes in vocalizations, respiration, swim speed, diving and foraging behavior, displacement, avoidance, and shifts in migration path (for reviews see Nowacek, 2007; Southall et al., 2007; Weilgart, 2007). For example, migrating gray whales *Eschrichtius robustus* slowed down and altered course at ranges of 1-3 km when exposed to low-frequency sounds associated with offshore oil industry. Half of the >3500 whales observed avoided exposure to continuous stimuli at levels >117-123 dB, and to airgun pulses at levels >170 dB (Tyack, 1993). On their summering grounds in Alaska, humpback whales *Megaptera navaeangliae* were reported to change orientation and move directly away from vessels within several kilometres (Baker & Herman, 1989). Common Minke whales *Balaenoptera acutorostrata* were even displaced from an area by an increased level of vessel traffic (Anderwald et al., 2013).

In order to minimize negative impacts from anthropogenic noise on marine animals, many environmental agencies have established guidelines for mitigation measures that are to be followed during seismic surveys, naval exercises, and pile-driving (Erbe, 2013; Dolman et al., 2009; Weir & Dolman, 2007). Visual monitoring is the primary (and often sole) method of animal detection, i. e. dedicated visual observers (Marine Mammal Observers, MMOs) monitor the ship's environ for the presence of marine mammals and arrange a shutdown of the sound source if an animal is detected inside a safety zone (Dolman et al., 2009; Weir & Dolman, 2007). However, activities like seismic surveys are often conducted continuously for weeks to months. Human observers have a limited ability to focus and a limited field of view, and visual observation is impossible during night-time. Passive acoustic monitoring (passively listening for vocalizations of marine mammals) is very limited for species that are largely non-vocal or not vocalizing at the time of mitigation (Dolman et al., 2009; Weir & Dolman, 2007). In contrast, infrared(IR)-based whale detection offers the possibility to detect whales round-the-clock, including night-time, with a 360°-view (Zitterbart et al., 2013).

Here, an infrared camera system installed on the research icebreaker *RV Polarstern* was used to record thermal video streams of free-ranging fin whales *Balaenoptera physalus* and humpback whales on an expedition to Antarctica in 2012-2013. The focus of this thesis was the evaluation of the behavioural response of the whales to the vessel by retrospective analysis of the thermal video recordings. In addition, the data collected with the IR system were compared to visual recordings collected concurrently by visual observers on board the ship. The comparison was based on the number of detected events, the calculated distances between a whale and the ship, and the ability to analyse the animals' behaviour.

2. Background

2.1 Sound terminology and underwater sound propagation

Sound is energy that travels as a compression wave through an elastic medium and causes particles to vibrate as it transfers from one to the next (Richardson et al., 1995). In fluids, these vibrations are in the direction of propagation and, therefore, are called longitudinal waves that transfer energy without transporting any mass. The positive peaks of a pressure wave correspond to locations where particle density is increased (compression) and the negative peaks to locations where particle density is decreased (rarefaction; Au & Hastings, 2008). These changes in pressure can be detected by the ear (Hatch & Wright, 2006). The frequency of a sound is the rate of vibrations in cycles per second (Hertz; Hz), where 1 cycle/s = 1 Hz, and determines the pitch of the sound (Marine Mammal Commission (MMC), 2007). A tone is a sound with a constant frequency continuing for a substantial time, while a pulse has a short duration and may comprise a broad range of frequencies (MMC, 2007). The wavelength (λ) of a sound is the distance a wave travels in one cycle and is equal to the speed of sound divided by its frequency. Hence, high-frequency sounds have shorter wavelengths than low-frequency sounds in the same medium (Hatch & Wright, 2007).

The energy of a sound is characterized using parameters like sound intensity and sound pressure (MMC, 2007). Sound intensity (I) is the acoustic power impinging on a surface perpendicular to the direction of sound propagation, i.e. the energy per second per unit area, usually given in W/m² (Dahl et al., 2007; Ketten, 1997). It is transformed to logarithmically scaled decibel (dB) units which are defined as ten times the base-10 logarithm of the ratio of the sound intensity to a reference intensity (Kinsler et al., 1982). Sound intensity is then referred to as sound pressure level (SPL; MMC, 2007). For sound in sea water, the reference pressure level is one microPascal (µPa), thus, units of dB re 1 µPa. The reference distance is one meter because the measured pressure level from a particular sound source decreases with distance from the source. Therefore, the specification of dB re 1 µPa @ 1 m is the source level (SL) of a sound source (hereafter only referred to as dB). This reduction in pressure level with distance is called transmission loss (Richardson et al., 1995). It may be considered to be the sum of loss due to spreading and loss due to absorption and attenuation (Au & Hastings, 2008). The simplest kind of spreading loss is spherical spreading loss. A sound source emits a signal of equal intensity in all directions. The intensity decreases as the square of range so that transmission loss increases as the square of range (Au & Hastings, 2008). Hence, if the sound pressure is measured at a distance from the sound source, this would be the received level (RL; Richardson et al., 1995).

Due to the logarithmic nature of the decibel scale, an increase in sound pressure level of 3 dB represents doubling the acoustic power (Hatch et al., 2008).

Sound pressure levels may vary over time so that measurements usually refer to a maximum (peak) level or to an average (root-mean-squared, rms) level (MMC, 2007). Since the range of frequencies of an underwater sound source may not be constant, its frequency bandwidth can be specified in decibel units for pressure spectral density dB re 1 µPa²/Hz which is called the spectral level (Dahl et al., 2007; MMC, 2007).

In water, sound travels with an average speed of 1530 m/sec, almost five times faster than through air (Urick, 1983). The speed of sound (*c*) is determined by the pressure and the density. In the ocean, the pressure increases with depth, and density in turn depends on temperature and salinity (Eckart, 1946). Thus, the sound velocity as a function of depth is a function of temperature, salinity and pressure (depth) and is not constant (Au & Hastings, 2008; Eckart, 1946). For each 1% increase in salinity, sound speed increases 1.5 m/sec; it increases 1.8 m/sec for each 100 m increase in depth and for each 1° decrease in temperature, velocity decreases 4 m/s (Ingmanson & Wallace, 1973). Thus, of these factors, temperature has the greatest influence on sound velocity (Eckart, 1946). An ocean sound profile is shown in Fig. 1. The profile can be divided into three main layers (Jensen et al., 1994). The oceanographic parameters in the upper ocean are primarily affected by diurnal and seasonal changes. During a warmer season or warmer part of the day, the temperature near the surface increases and so does the sound velocity. The *mixed layer* has a rather constant temperature caused by continuous mixing due to wind and wave activity (Jensen et al., 1994). In the *main thermocline,* sound velocity decreases with depth as a result of the negative temperature gradient. Underneath the thermocline lies the *deep isothermal layer* that extends to the ocean bottom. The water temperature is rather constant, so that the sound velocity increases only slightly with depth due to increasing pressure. Between the main thermocline and the deep isothermal layer, the sound velocity reaches its minimum (Au & Hastings, 2008; Jensen et al., 1994). That is where the Deep sound channel or SOFAR (*SO*und *F*ixing *a*nd *R*anging) channel is located which was discovered by Ewing and Worzel (1948). The depth of this sound channel varies from over 1600 m in warm waters to 100 m in colder waters. At the ice edge in Polar Regions, it can reach the surface and become a surface sound channel (Hatch & Wright, 2007). It revealed the possibility of long-distance sound propagation that was demonstrated in 1960, when detonations at the depth of the sound channel axis off Perth, Australia, were recorded 20,000 km far away by a hydrophone in Bermuda (Munk et al., 1988). Following Snell's law, the increasing sound velocity above and below the minimum causes the sound waves to refract, and focuses the sound like a lens. This leads to a cylindrical spreading of the sound and prevents reflection and adsorption of by the sea surface and the sea floor allowing sound to propagate much further along the SOFAR channel's axis (Williams & Horne, 1967).

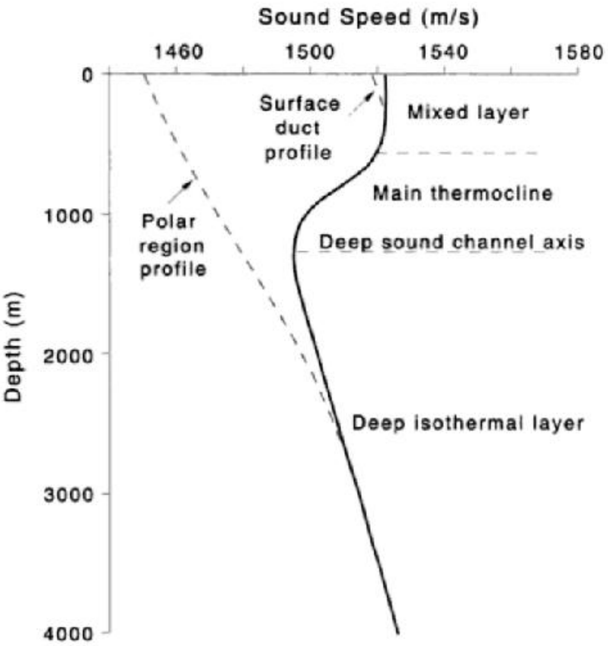


Fig. 1: Speed profiles for different oceanographic conditions. In polar waters, the water at the surface is near freezing. This causes an inverse trend with decreased density and velocity (Jensen et al., 1994).

Speed of sound in sea water is the same for all frequencies. Regardless of the medium, low-frequency sounds travel further than high frequency sounds because their energy is absorbed more slowly, i. e. they experience little attenuation. For this reason, especially low-frequency can travel over hundreds and thousands of kilometers in the deep sea channel (Hildebrand, 2009; Hatch & Wright, 2007; Urick, 1983). Additionally, louder sounds have more energy to disperse over distance from the source than softer sounds, allowing them to travel over a greater distance (Hatch & Wright, 2007).

In general, ambient noise ("the overall background noise caused by all sources such that the contribution from a single specific source is not identifiable"; NRC, 2003) differs in shallow and in deep waters. Deep water ambient noise means that there is no bottom interaction of sound from distance sources (typically commercial shipping; Dahl et al., 2007; Wenz, 1962). This happens if there is a critical depth at which the sound velocity is equal to the velocity at the sea surface. The critical depth is located at approximately 4000 m below which the ambient noise is reduced but does not vanish altogether (Dahl et al., 2007). Wenz (1962) stated that shallow water ambient noise exceeds deep water ambient noise levels by about 5 dB at the same frequency and the same wind speed.

2.2 Anthropogenic noise sources in the ocean

Ambient noise is defined by the National Research Council (NRC, 2003) as “the overall background noise caused by all sources such that the contribution from a single specific source is not identifiable”. The earliest studies on underwater ambient noise were done during World War II and established surface-ship radiated noise, sea surface noise and the sounds of marine animals as major contributor to the ambient noise field (Dahl et al, 2007). Nowadays, sound in the ocean is generated by a variety of both natural and anthropogenic sources (Hildebrand, 2009). Natural sound sources include breaking waves, wind, rain, ice, thunder and lightning, earthquakes, and marine animals, while shipping, seismic exploration, naval exercises and industrial activities are major human made sound sources (Hildebrand, 2009; Hatch & Wright, 2007; Hildebrand, 2005). Different sound sources are dominant in each of 3 frequency bands, defined as low (10 to 500 Hz), medium (500 Hz to 25 kHz) and high (>25 kHz) (Hildebrand, 2009). Based on deep-water studies in the Northeast Pacific, low-frequency background noise has increased by approximately 12 dB since the 1960ies (McDonald et al., 2006; Andrew et al.,

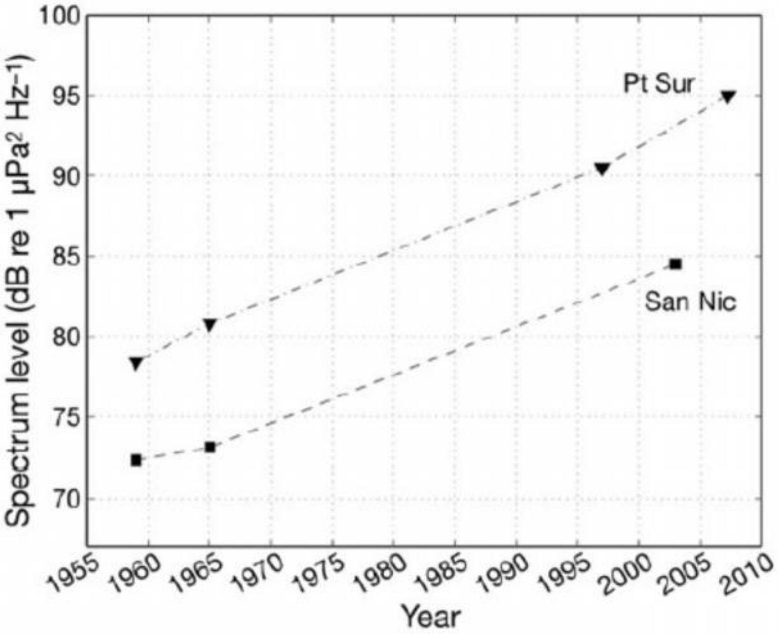


Fig. 2: Historical ambient noise data from the north-eastern Pacific suggesting an increase of approx. 3 dB in each of the past four decades. Data from the U.S. Navy hydrophone arrays near Pt Sur and San Nicolas Island (Wenz, 1969, 1968, 1961) and recent measurements (Cocker, 2008; McDonald et al., 2006; Andrew et al., 2002) compiled by Hildebrand (2009).

2002) which equals a doubling in deep water over each of the past four decades. Hildebrand (2009) even suggests an overall increase of at least 20 dB in low-frequency ambient noise compared to preindustrial conditions (Fig. 2). This increase has been attributed primarily to commercial shipping, followed by seismic exploration and sonars (Hildebrand, 2009; Ross, 1976). Tab. 1 gives sound characteristics of major anthropogenic noise sources.

Tab. 1: Sound characteristics of major anthropogenic sound sources (adapted from MMC, 2007, based on Hildebrand, 2005).

Sound source	Primary frequency range	Sound pressure levels	Distribution	Total energy
Commercial shipping	5-100 Hz	150-195 dB re 1µPa²/Hz @ 1 m	great circle routes, coastal and port areas	3.7 x 10^{12}
Seismic airgun arrays	5-150 Hz	up to 259 dB	variable with emphasis on continental shelf areas with oil and gas	3.9 x 10^{13}
Naval sonars	100-500 Hz (SURTASS LFA) 2-10 kHz (Mid-frequency sonar)	235 dB 235 dB	variable below 70° latitude variable with emphasis on coastal areas	2.6 x 10^{13}
Fisheries sonars	10-200 kHz	150-210 dB	variable, primarily coastal and over continental shelf	unknown
Research sonars	3-100 kHz	up to 235 dB	variable	unknown
Acoustic deterrents, harassment devices	5-16 Hz	130-195 dB	coastal	unknown

Commercial shipping has been intensifying in number, size, speed, and horsepower of the vessels over the last decades and is distributed over all world's oceans (Hildebrand, 2009, 2005; NRC, 2005; Urick, 1983; Ross, 1976), so that it dominates the average deep-water conditions in the 20-200 Hz band all over the planet (Urick, 1983). Near shipping lanes (McDonald et al., 2006; Andrew et al., 2002) and in the Northern Hemisphere in general (Cato, 1976) noise levels are higher. A map of the main global shipping routes is shown in Fig. 3. Although higher frequencies are possible, most of the noise from large ships has a frequency of 5-200 Hz and is produced at levels between 160 and 180 dB (MMC, 2007; Richardson et al., 1995). In general, noise levels from ships increase with increasing size and speed of the vessels (Hildebrand, 2009; Gray & Greeley, 1980; Tab. 2). A single oil tanker has been estimated to have an average area of ensonification at the 120 dB level of more than 2,000 km² (Hatch et al., 2008).

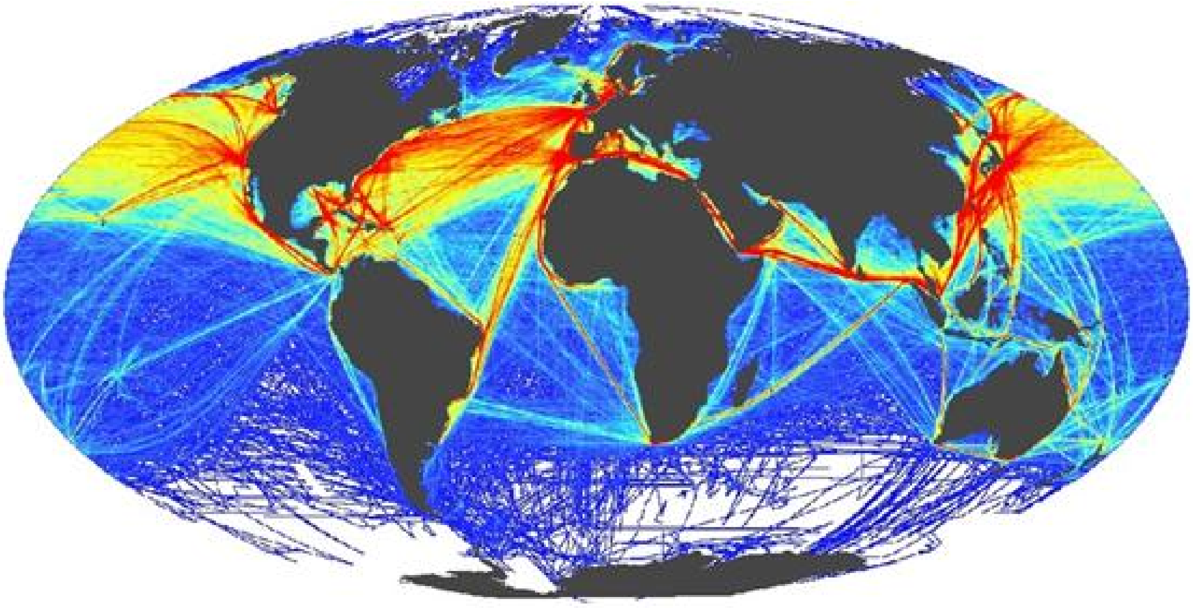


Fig. 3: Main commercial shipping routes of the world's oceans (Halpern et al., 2008).

Tab. 2: Source levels from commercial vessels for several frequencies (adapted from Emery, 2000). An empirical equation based on Ross (1976) was used to calculate approx. source levels on the basis of measured source levels of ships and their individual speeds and lengths. As an average ship was defined as one with a speed of 12 kn and a length of ca. 92 m (300 feet), source levels for different types of ships and for several frequencies were obtained.

			Source levels for several frequencies [dB re 1 µPa m]				
Ship type	**Length [m]**	**Speed [kn]**	**10 Hz**	**25 Hz**	**50 Hz**	**100 Hz**	**300 Hz**
Supertanker	244-366	18-22	185	189	185	175	157
Large tanker	153-214	15-18	175	179	176	166	149
Tanker	122-153	12-16	167	171	169	159	143
Merchant	84-122	10-15	161	165	163	154	137

* Adapted from Research Ambient Noise Directionality (Model)(RANDI) Source Level model.

Vessels generate several types of noise. Machinery noise comprises that part of total noise of the vessel caused by the ship's diesel engines, main motors, generators, pumps, etc. (Urick, 1983). Hydrodynamic noise is radiated noise originating in the irregular flow of water past the vessel moving through it and causing noise by a variety of hydrodynamic processes (Urick, 1983). At very low-frequencies, in the 0.1-10 Hz range, propeller noise is the dominant noise source (Lurton, 2002). Propeller noise refers to cavitation at or near the propeller as well as propeller-induced resonant hull excitation. Cavitation noise is caused by every propeller-driven ship. It is the result of the formation and implosion of water cavities caused by the decrease andincrease in pressure as water moves across rotating propeller blades. The bubbles quickly collapse, thereby creating a loud acoustic sound. Cavitation causes broadband noise as a result of growth and collapse of a vast amount of individual cavitation bubbles in the water (International Maritime Organization (IMO), 2013*a*; Lurton, 2002; Urick, 1983). The noise level from cavitation depends largely on the propeller's rotational speed and the mechanical character of the propulsion system (Lurton, 2002). Additionally, some icebreakers are equipped with a so-called bubbler system which blows high-pressure air into the water in order to push floating ice away from the ship (Erbe & Farmer, 2000). Thereby, noise is caused by the air bubbles that are introduced into the sea surface.

When the propellers of a vessel are located above keel depth, acoustical shadowing (also called bow null effect) occurs (Gerstein et al., 2005; Fig. 4.). In this case, sound rays from the propeller are prevented from projecting forward by the ship's hull and are, instead, reflected from the stern. Only frequencies with wavelengths larger than stern dimensions can diffract around the hull. Due to this effect, the quietest area near an approaching vessel is at the surface directly ahead of the ship's path (Gerstein et al., 2005). The size and geometry of the shadow zone can vary depending on hull construction and/or propulsion type (Allen et al., 2012). A submerged hydrophone recording sound at a few meters depth near a vessel's path with the vessel passing by it will record low-frequency sounds of the ship. As the ship passes, the frequency range of the propeller noise will increase until the geometrical diffraction limit is reached (Blue & Gerstein, 2005).

Even though noise from seismic surveys, sonars and other noise sources might be more limited in their distribution compared to the worldwide vessel traffic, they also induce a significant amount of acoustic energy into the oceans. The US Navy's low-frequency active (LFA) sonar which is used to detect submarines has been estimated to cause noise levels of 120 dB in an area of 3.9 million km^2 (Johnson, 2003). Seismic surveys are used to discover oil and gas deposits under the sea floor, and generate sound pulses in intervals over the course of days and weeks (Gordon et al., 2004). While operating, a single survey can result in an elevation of noise

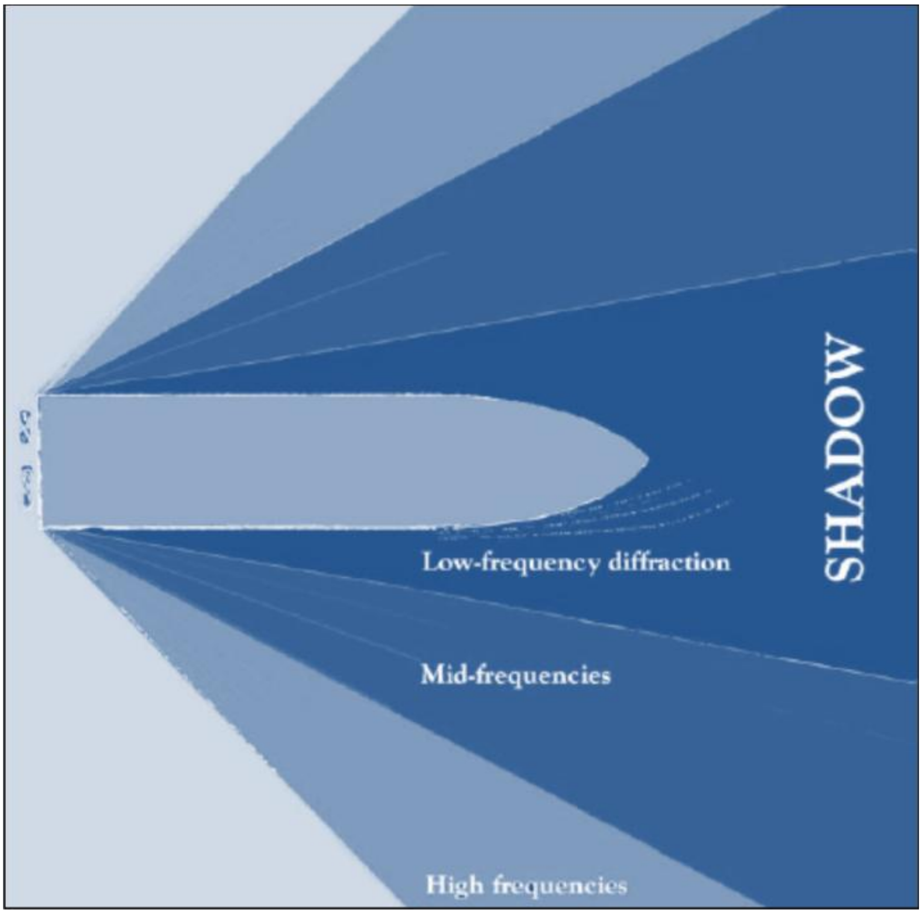


Fig. 4: Simplified scheme of acoustical shadowing and diffraction of propeller noise around a ship's hull (adapted from Gerstein et al., 2005). Dominant frequencies are indicated.

levels by 20 dB in a region of approximately 300,000 km² (International Whaling Commission (IWC), 2005). Industrial activities involve further anthropogenic noise sources including drilling, pile-driving, and offshore wind farms, with the highest acoustic energy typically from 20 to 1000 Hz (Greene, 1987). Acoustic deterrent devices (ADDs) and acoustic harassment devices (AHDs) emit sounds at mid to high frequencies in order to keep marine mammals away from aquaculture facilities or fishing gear (Pepper et al., 2004). AHDs generate rather high source levels (205 dB) compared to ADDs (150 dB; Hildebrand, 2009), and e.g. displaced killer whales *Orcinus orca* from habitat in British Columbia, Canada, over several years (Morton & Symonds, 2002). Also, research contributes to ocean noise, for instance the ATOC (acoustic thermometry of ocean climate) project in the 1990s. In order to study ocean climate and thus global warming, loud sounds were introduced into the ocean to receivers located over 10,000 km away (Weilgart, 2007*a*).

By the definition of the United Nations Convention on the Law of the Sea (UNCLOS; United Nations Division for Ocean Affairs and the Law of the Sea, 1982), ocean noise can legally be treated as pollutant (McCarthy, 2004). Although there is no specific international legislation for the regulation of noise in the sea, there is recognition that responsibility for addressing the situation lies within the mandate of the UN and its structures (IMO, 2009; International Union for Conservation of Nature (IUCN), 2004).

2.3 Ecology of baleen whales

The order Cetacea is divided into two suborders, the mysticetes or baleen whales, and the odontocetes or toothed whales. While the odonocetes comprise the sperm whales, beaked whales, dolphins and porpoises, the mysticetes consist of the right whales and the rorquals. There are 14 species of baleen whales recognized in four different families by the IUCN (2014; Tab. 3). They are typically large, pelagic planktivores (Gaskin, 1976) that are found in all oceans of the world (e. g. Clapham & Mead, 1999; Gambell, 1985). Two species of the balaenopterids are considered in this thesis, the Southern Hemisphere humpback whale *Megaptera novaeangliae* and the fin whale *Balaenoptera physalus* (Fig. 5).

With a maximum recorded length of 17.4 m (Chittleborough, 1965), the humpback whale is smaller than the fin whale which can reach an average length of 21.2 m in the Southern Hemisphere (Nishiwaki, 1950). In all baleen whales, females typically grow larger than males (Chittleborough, 1965), presumably due to the bioenergetic demands of reproduction (Ralls, 1976). The most characteristic features of humpback whales are their remarkably long flippers which are about one third of their body length (Whitehead, 1981). They are well known for their fluke-ups before diving and spectacular aerial behaviours such as breaching (Félix & Haase, 2001; Helweg & Herman, 1994; Whitehead, 1983). The fin whale has a slender and much more streamlined appearance than the humpback whale with a prominent dorsal fin (Reeves et al., 1998). With a recorded swimming speed of 40 km/h, it is the fastest swimmer of baleen whales (Heckel & Schramm, 2005).

As the name indicates, baleen whales are characterized by several hundred ventral plates of baleens. Balaenopterids or rorquals, of which humpback and fin whales are members, feed by lunging forward to engulf a single mouthful of water and schooling or otherwise aggregated prey which is then filtered by these plates as the tongue moves backward and downward (Lambertsen, 1983; Kawamura, 1980). When lunging, they can engulf a mass of water that represents almost 70 % of their body mass (Pivorunas, 1979). Balaenid whales, on the other hand, feed by continuously filtering food (Watkins & Schevill, 1979; Ingebrigtsen, 1929).

Tab. 3: Taxonomic classification of the 14 species of mysticetes currently recognized by the IUCN (2014).

Order Cetacea		
Suborder Mysticeti		
Family	**Species**	**Common name**
Balaenidae	*Balaena mysticetus* Linnaeus, 1758	Bowhead whale
	Eubalaena asutralis (Desmoulins, 1822)	Southern Right whale
	Eubalaena glacialis (Müller, 1776)	North Atlantic Right whale
	Eubalaena japonica (Lacépède, 1818)	North Pacific Right whale
Balaenopteridae	*Balaenoptera acutorostrata* Lacépède, 1804	Common Minke whale
	Balaenoptera bonaerensis Burmeister, 1867	Antarctic Minke whale
	Balaenoptera borealis Lesson, 1828	Sei whale
	Balaenoptera edeni Anderson, 1878	Bryde’s whale
	Balaenoptera musculus (Linnaeus, 1758)	Blue whale
	Balaenoptera omurai Wada, Oishi & Yamada, 2003	Omura’s whale
	Balaenoptera physalus (Linnaeus, 1758)	Fin whale
	Megaptera novaeangliae (Borowski, 1781)	Humpback whale
Eschrichtiidae	*Eschrichtius robustus* (Lilljeborg, 1861)	Gray whale
Neobalaenidae	*Caperea marginata* (Gray, 1846)	Pygmy Right whale

Baleen whales take a variety of prey. Several species of Euphausiids, notably *Euphausia superba,* have been considered as the primary food source in Antarctic waters (Nemoto, 1970). However, besides plankton they also feed on a variety of small schooling fish, including capelin *Mallotus villosus* (Whitehead, 1983, 1981), herring *Clupea* spp. (Watkins & Schevill, 1979), mackerel *Scomber scombrus* (Geraci et al., 1989), and sand lance *Ammodytes* spp. (Payne et al., 1990).

Most mysticetes are highly migratory and travel annually between breeding grounds in low and feeding grounds in high latitudes (Boyd, 2009; Dalla Rosa et al., 2008; Širovic et al., 2004; Dawbin, 1966). In the Southern Hemisphere, the migration allows to exploit the high productivity

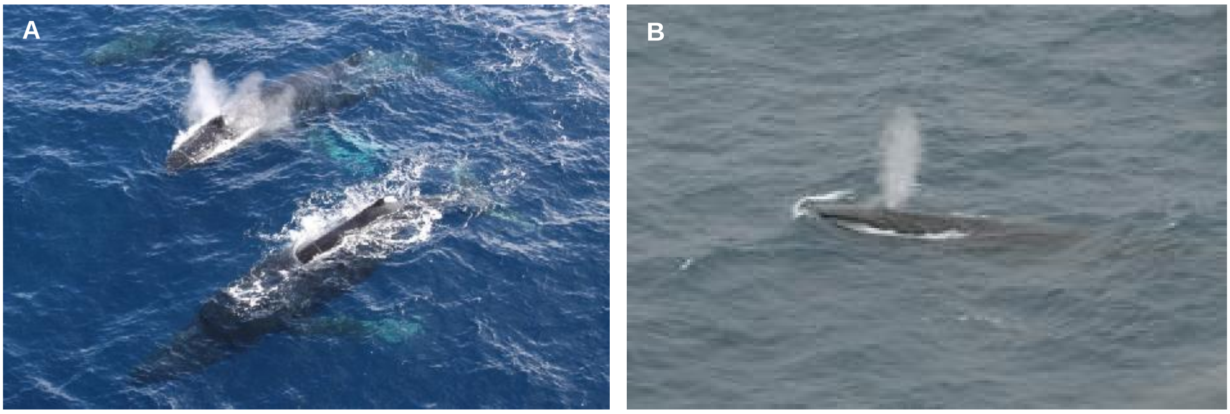


Fig. 5: The two baleen whale species considered in this thesis, (A) the Southern Hemisphere humpback whale *Megaptera navaeangliae* (© I. van Opzeeland / AWI) and (B) the fin whale *Balaenoptera physalus* (© H. Verdaat / AWI).

in the Southern Ocean during the austral summer and spring, and to mate and calve in relatively unproductive temperate or tropical waters during winter (Corkeron & Conner, 1999; Dawbin, 1997). The factors driving these migrations that include the longest known annual movement of any mammal (Stone et al., 1999) are still poorly understood (Corkeron & Conner, 1999). The most likely hypotheses focus on benefits for calf growth and survival from the calm and warm waters and a reduced risk of predation from killer whales *Orcinus orca* in the breeding grounds (Corkeron & Connor, 1999). However, there is no consent on any hypothesis so far (e. g. Mehta et al., 2007). For males, the opportunity to encounter and mate with females is thought to drive the migration movement (Corkeron & Connor, 1999). Examinations of whaling catches of humpback whales showed a staggering of sexual and maturational classes on the southward migration that is broadly reversed on the northward migration (Dawbin, 1966; Chittleborough, 1965).

It has been noted for various baleen whale species that a part of the population remains in the high latitude feeding grounds during winter in both hemispheres (see Van Opzeeland et al., 2013; Corkeron & Connor, 1999). In humpback whales, some females (Craig & Herman, 1997; Brown et al., 1995) as well as juveniles of unknown sex (Clapham et al., 1993; Swingle et al., 1993; Straley, 1990) do not migrate each year. Brown et al. (1995) have hypothesized that many non-breeding females remain on the feeding grounds, presumably to avoid the energetic costs of migration. While feeding is believed to not occur on the breeding grounds (Clapham, 2000), humpback whales in the Southern Hemisphere have been documented to feed on both the southern and northern migration (Dawbin, 1956 and Stockin & Burgess, 2004, respectively).

Recent studies suggest that feeding on migration is not only an opportunistic behaviour (Owen, 2014; Stamation et al., 2007).

Baleen whales have a gestation period of ten to twelve months that fits with the annual seasonal cycle and allows conception and birth at the same time of the year (Whitehead & Mann, 2000; Chittleborough, 1958). The peak birth month in the Southern Hemisphere is August (Chittleborough, 1958). Calves follow their mothers to the feeding grounds when only a few weeks old (Clapham, 2000). Duration of lactation ranges from six to approximately eleven months, before they feed independently (Clapham, 2000; Whitehead & Mann, 2000). Even though separations of calves from their mothers in the autumn following their birth have been reported in humpback whales (Baraff & Weinrich, 1993), the majority of the mothers stay with their calf until its second winter (Clapham, 2000). There is an interbirth interval of two or three years in mysticetes increasing with body size (Whitehead & Mann, 2000).

During the austral summer, most mysticetes show a circumpolar distribution in the waters surrounding the Antarctic continent. Local aggregations of baleen whales can be observed which are likely influenced by environmental conditions and species-specific habitat preferences (Bombosch, 2013; Boyd, 2009; Thiele et al., 2000; Kasamatsu et al., 1996). It remains unknown, whether they also reflect some underlying social structure. In general, small unstable groups (also called pods) seem to be most common in mysticetes (Clapham, 2000). However, humpback whales often travel in pairs or triplets (Whitehead, 1983) and long-term associations have been documented (Weinrich, 1991).

Due to the seasonal opposition of the hemispheres, whale populations in the Northern Hemisphere are feeding while their Southern counterparts are breeding, and vice versa (Clapham, 2000). Populations from different hemispheres diverge in behaviour, morphology, and vocalizations. It is well known, for example, that individuals of the Balaenopteridae family are larger in body size in the Southern Hemisphere (Brodie, 1975; Mayr, 1965). More recently, genetic analyses have underpinned differences in populations in both humpback and fin whales (Jackson et al., 2014 and Archer et al., 2013, respectively) and suggest a need for revision into subspecies.

Most of the species of great whales were intensively exploited during the past centuries and the industrial whaling drastically reduced their abundance (Whitehead et al., 2000). After the opening of the rich whaling grounds in the Southern Ocean in 1904, approximately two million whales were killed during the following six decades (Clapham & Baker, 2002). Some populations were effectively wiped out (Clapham, 2000), and many others are still well below their pre-exploitation levels (Clapham et al., 1999), even though a worldwide moratorium on commercial whaling came into effect in 1986 (Clapham & Baker, 2002). About 750,000 fin whales were caught in the Southern Hemisphere (Clapham & Baker, 2002) and this species is still listed as endangered, like several other mysticetes, by the IUCN (2014). There is no recent abundance estimation, as the most recent estimate of 15,178 animals for the Southern Hemisphere is based on data from 1979-88 (Reily et al., 2013).

Few other populations, in contrast, have been able to recover from the extreme decline, e. g. the east Australian humpback whale. After 200,000 animals were killed in the Southern Hemisphere until the worldwide protection in 1966 (Reily et al., 2008; Clapham & Baker, 2002), Paterson et al. (1994) showed an average annual increase of 11.7 % (95% CI 9.6-13.8 %) in this population between 1984 and 1992. In 2008, the world population was estimated at over 60,000 animals, increasing by tendency, and is now listed as “least concern” (Reily et al., 2008).

Even though whaling continues until today, e. g. commercial whaling by Norway and Iceland (either under reservation to the moratorium or under rejection of it; Higham & Lusseau, 2007), there are several other anthropogenic threats which potentially affect some or all large whale species and other cetaceans (Whitehead et al., 2000; Clapham et al., 1999).

Habitat loss and degradation are serious threats with a number of causes, including recreational and commercial shipping, oil spills, coastal development (Whitehead et al., 2000). The “food web competition” (Trites et al., 1997) between fishing fleets and marine mammals is difficult to assess, however, major effects of intensive human exploitation on prey abundance have been shown in many areas (Payne et al., 1990; Brown & Halliday, 1983). Pollution affects organisms by impairing the reproductive system and weakening the immune system, and is assumed to play a role in some die-offs of cetaceans (see Whitehead et al., 2000). Odonotocetes seem to be more vulnerable to pollution than baleen whales, though, presumably due to bioaccumulation along the food chain (O‘Shea & Brownell, 1994). Also, incidental effects kill many thousand animals every year. While smaller cetaceans like dolphins are more susceptible to by-catch (IWC, 1994), baleen whales like the Northern right whale and the fin whale are typically the victims of ship strikes (Laist et al., 2001; National Marine Fisheries Service (NMFS), 1991). It is largely unknown how climate change will affect cetaceans (Whitehead et al. 2000). The incidence and degree of impact from these threats varies substantially among species and populations (Clapham et al., 1999).

It is important to note the potential of these threats to interact with one another and with natural stressors (Whitehead et al., 2000). Additionally, already small and endangered populations are more vulnerable to negative impacts (Clapham et al., 1999). As described in 1.2., noise is a by-product of various human activities and, for example, could pose an impediment for members of a depleted population to find mates (Whitehead et al., 2000).

The basic goal of conservation is the prevention of harm from anthropogenic activities on marine mammal populations (NRC, 2005). For effective conservation, we need to not only understand the demands of species on their environment but also how cetaceans are affected by human activities, the consequences at the population-level, and how to mitigate in the best way possible.

2.4 The acoustic sense of baleen whales

Due to the physical characteristics of the underwater environment sound is the most efficient information channel in the ocean (Tyack, 2000). Hence, as obligate marine animals, it is no surprise that cetaceans have evolved a sophisticated auditory sense and rely on sound as principal mean for underwater communication and sensing (Weilgart, 2007; Wartzok & Ketten, 1999). They use sound for communication, individual recognition, predator avoidance, prey capture, orientation, navigation, mate selection, and mother-offspring bonding (Tyack, 2000; Wartzok & Ketten, 1999).

The cetacean ear is the most fully adapted auditory system of marine mammals. However, there are anatomical differences among modern odontocete and mysticete ears in relation to their role in species-specific frequency ranges. These, in turn, are correlated with differences in habitat and feeding behaviour (Ketten, 1992). Thus, cetaceans can be divided into high and low frequency sound producers, coinciding with the two suborders because mysticete vocalizations are significantly lower in frequency than those of odontocetes (Wartzok & Ketten, 1999).

2.4.1 Anatomy of the cetacean ear

Hearing capacities are the result of the integrated components of the whole ear (Wartzok & Ketten, 1999). The auditory anatomy of cetaceans follows the basic mammalian pattern, with some adaptations for underwater hearing. The ear is divided into three sections: the outer ear, the middle ear, and the inner ear or cochlea (Au & Hastings, 2008; Wartzok & Ketten, 1999). The fact that cetaceans do not have an auricle has been attributed to the need of a streamlined body shaped (Ketten, 1995). The tympanic membrane (the eardrum) separates the outer and inner ear. The air-filled external ear canal from terrestrial mammals that transmits airborne sound to the inner ear is missing in cetaceans, as the sounds they perceive are not airborne. The inner ear converts sound energy into neural signals which the auditory nerve transmits to the central nervous system. When sound enters the inner ear via the oval window, the acoustic energy causes vibrations of a membrane, called basilar membrane. The vibrations deform acoustic receptor hair cells which generate neural signals (Au & Hastings, 2008; Wartzok &

Ketten, 1999). The basilar membrane holds the key to hearing in mammals. From the basal end, near the oval window, towards the apical end, the characteristics of the membrane change which is the most important condition for frequency discrimination (Wever et al., 1971). In cetaceans, the basilar membranes show substantial differences between species (Ketten, 1994). Hair cells located at different positions along the basilar membrane are sensitive to different frequencies. Their rate of firing is proportional to the amount of acoustic energy in the frequency band to which they are sensitive (Au & Hastings, 2008). The density of neurons – also called ganglions - that receive input from sensory cells along the basilar membrane likely determines how good different frequencies can be discriminated. Compared to other mammals, cetaceans have an unusually high density of ganglions (Ketten, 1990). Furthermore, they seem to have faster auditory processing capabilities, and their brain is dominated by the temporal lobes which are responsible for auditory processing (Ketten, 2002). However, little is known about the acoustic paths in baleen whales (Ketten, 1992).

2.4.2 Sound production and vocalizations

Over five decades after the first identification of vocalizations from baleen whales (Schevill et al., 1964), the mechanism of sound production has remained a mystery to the most part. An internal mechanism involving the mouth and respiratory system and particularly the larynx was suggested by Clark (1990). In a more recent study, a vocal fold homolog which is assumed to be associated with sound generation was found in the larynx of six baleen whale species and offers a new insight into the exact mechanism (Reidenberg & Laitman, 2007).

Sounds have been recorded from at least twelve baleen whale species (Risch et al., 2014; Clark, 1990). Their vocalizations can be categorized regarding their context and their assumed function (e.g. Edds-Walton, 1997) or regarding their sound characteristics (e.g. Clark, 1990). Due to difficulties to study sounds in the context they are used in, their functions still remain largely unknown.

Clark (1990) divided vocalizations of baleen whales into two sections, songs and calls. Calls, in turn, can be further divided into (1) simple calls, (2) complex calls, and (3) clicks, pulses, knocks and grunts, depending on their sound characteristics. Calls of the same category do not necessarily fulfil the same biological function (Clark, 1990).

Besides the different types of calls, four mysticetes have been recorded to produce songs, the blue whale (Alling et al., 1991; Alling & Payne, 1991), the fin whale (Watkins et al., 1987), the bowhead whale (Ljungblad et al., 1982), and the humpback whale (Payne & McVay, 1971).

Clark (1990) defined songs as “sequences of notes occurring in a regular sequence and patterned in time”.

Edds-Walton (1997) divided vocalizations according to the context they were used in, with focus on interactions or acoustic exchanges among conspecifics. The sounds were divided into (1) contact calls of single animals outside the breeding season, including cow-calf pairs, (2) vocalizations during the breeding season (often called songs) and (3) calls produced by active groups of whales reported in both breeding and feeding areas (Edds-Walton, 1997).

Vocalizations are known to be an important element of behaviour in both breeding and feeding grounds as well as during migration (Edds-Walton, 1997). Signals from both blue and fin whales, for example, are likely to play a role in mating and feeding behaviours (Oleson et al., 2007; Croll et al., 2002; McDonald et al., 2001; Watkins et al., 1987), and songs of humpback whales are thought to be a reproductive display by males (Tyack & Whitehead, 1983). Responses to conspecifics have been documented in several baleen whale species suggesting that all mysticetes communicate similarly (Edds-Walton, 1997).

Certain baleen whale calls are potentially audible over ranges of hundreds of kilometres (Stafford et al., 1998; Clark, 1995; Cummings & Thompson, 1971; Payne & Webb, 1971). Long-range propagation might be important for communication with conspecifics (Payne & Webb, 1971) and offers many advantages for highly migratory species like mysticetes that range across oceans (Edds-Walton, 1997). For depleted populations that have not recovered from the exploitation of commercial whaling, communication over long distances could be crucial for species survival (Širović et al., 2007). However, it is unclear whether whales actually communicate over such long ranges (Tyack, 2000). The longest distance over which whales have been documented to respond to sounds of conspecifics is approximately 10 km (Tyack & Whitehead, 1983; Watkins & Schevill, 1979). Selective forces may have driven the evolution of loud vocalizations (Tyack, 2000). For example, if signals are involved in competitive behaviours between males, and the louder vocalizer has an advantage, selection could favour signals that are louder than necessary to be detected by the intended receiver (Tyack, 2000). Indeed, baleen whale vocalizations are also among the loudest sounds in the animal kingdom (Sears & Perrin, 2009; Cummings & Thompson, 1971). Off the Western Antarctic Peninsula, calls of blue and fin whales were located up to a range of 200 and 56 km, respectively (Širović et al., 2007). The average source level of the blue whale calls was 189±3 dB over 25-29 Hz and 189±4 dB over 15-28 Hz for fin whale calls.

Besides communication, long-range vocalizations of baleen whales have also been supposed to function for orientation, navigation, and topological imaging (George et al., 1989; Ellison et al., 1987; Thompson et al., 1979; Payne & Webb, 1971). Even though high-frequency echolocation has only been documented in odontocetes (Tyack, 2000), there is evidence that low-frequency sounds of mysticetes could have a similar function. Low-frequency calls from blue and fin whales are assumed to produce echoes from seamounts hundreds of kilometres away (Clark, 1993). The hypothesis of whales using low-frequency sounds for echolocation has never been tested; however, further studies have shown that vocalizing bowhead whales avoid floes of deep ice at ranges much greater than the underwater visibility (Clark, 1989; George et al., 1989). Low-frequency calls from migrating bowhead whales could cause echoes from deep-keeled ice allowing the whales to detect and avoid the ice floes (Clark, 1989; George et al., 1989; Ellison et al., 1987). McDonald et al. (2005) suggest that fin whales are able to measure sound speed profiles in the ocean by countercalling among several animals. Tyack (2000) concludes that even if vocalizations are primarily used for communication, echoes from the sounds could also be used for orientation and navigation. In highly migratory animals like mysticetes this function seems reasonable and useful (Tyack, 2000).

2.4.3 Hearing in baleen whales

Until recently all of our knowledge about hearing in cetaceans had been obtained from studies on odontocetes since the 1960s. While audiograms (function of auditory detection threshold versus frequency) are available for a range of toothed whales (e. g. Atlantic bottlenose dolphin *Tursiops truncatus* (Johnson, 1967), harbor porpoise *Phocoena phocoena* (Andersen, 1970), false killer whale *Pseudorca crassidens* (Thomas et al., 1988)), the hearing sensitivity of baleen whales has never been tested (Tyack, 2000). Different approaches were used to derive estimations of the hearing sensitivity, e.g. Ketten (1994) used a comparative anatomy approach by deriving estimates from data about the correlation between inner ear morphometry and hearing sensitivity from audiograms of both terrestrial and aquatic species to derive estimates of hearing ranges for whales. The inner ears of baleen whales were apparently specialized for low-frequency hearing, and the range of best hearing was estimated to be of approximately 20-200 Hz (Ketten, 1994). The upper range for most mysticetes has been predicted to extend to 20-30 kHz (Ketten, 2002).

In a recent study, Cranford & Krysl (2015) generated synthetic audiograms (Fig. 6) using simulations derived from X-ray computed tomography (CT) scans of a fin whale’s head revealing two sound reception mechanisms. A predominant *bone conduction mechanism* seems largely responsible for the low-frequency sound reception. The hearing apparatus is excited by vibrations of the tympano-periotic complex (TPC) that consists of two exceptionally dense bones (Ketten, 2002). These vibrations are caused by deformations of the whale’s skull as sound waves are propagating through its head. A second mechanism, *the pressure mechanism*, describes the direct pressure on the tympanic bulla from the sound waves reaching the TPC via the seawater and multiple soft tissue pathways. Since the anatomical characteristics of the skull are the same in all mysticetes (Ekdale et al., 2001) similar sound reception mechanisms may be common to all baleen whales (Cranford & Krysl, 2015). The dashed box in the predicted audiogram (Fig. 6) shows the region of best hearing between 20 Hz and approx. 10 kHz where the sound pressure level drops by ~40 dB.

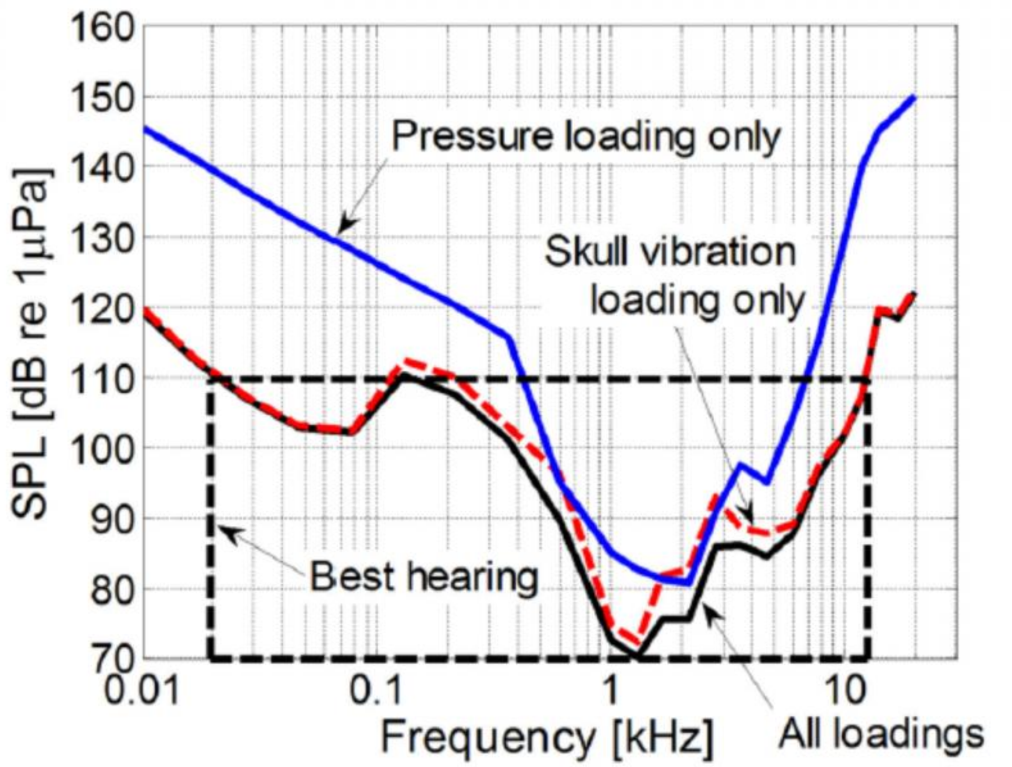


Fig. 6: Synthetic audiograms for a small fin whale (Cranford & Krysl, 2015). The blue line indicates the audiogram for the pressure mechanism. The dashed red line indicates the audiogram for the dominant bone conduction mechanism. The solid black line represents the combined audiograms for both mechanisms. The dashed black box indicates the region of best hearing.

2.5 Impact of anthropogenic ocean noise on cetaceans

Using sound as principal mean for underwater communication and sensing, ocean noise pollution is of special concern for cetaceans (Weilgart, 2007*b*; Wartzok & Ketten, 1999). Continuous noise is part of the environment of huge number if cetaceans at any given time (Whitehead et al., 2000), and as low-frequency specialists, mysticete whales might be particularly at risk from noise pollution from still increasing commercial shipping and other low-frequency sounds (Clark et al., 2009).

Initial concerns were raised by studies beginning in the late 1970s that revealed changes in the movements, dive patterns, and other behaviour of belugas *Delphinapterus leucas* and bowhead whales caused by sounds associated with offshore oil and gas exploration and development in Canada and Alaska (Awbrey et al., 1983; Burns et al., 1982, Fraker & Fraker, 1981). Further concerns were raised by the US Navy's Low-Frequency Active Sonar (LFAS) and Mid-Frequency Active Sonar (MFAS) which has been linked to a series of mass standings between 1996 and 2002 and physical trauma to whales and dolphins (see Craig, 2009). There are at least four primary concerns on how cetaceans might be affected by exposure to anthropogenic noise which will be further described below: permanent threshold shifts (PTS), temporary threshold shifts (TTS), acoustic masking and behavioural disturbance (Nowacek et al., 2007; Fig. 7). Even injury and death have been reported as result of sound exposure (e.g. Ketten et al., 1993). The effects of noise and the range over which they occur depend on the characteristic of the sound, i. e. pressure level, spectral distribution, duration etc. (Erbe, 2013).

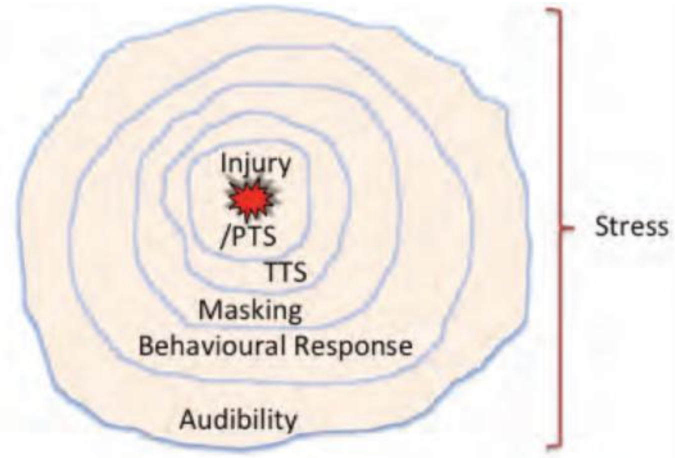


Fig. 7: Potential zones of impact around a noise source (red star; Erbe, 2013). Different distances for the different effects define the areas for each zone. With decreasing distance from the source, impacts might include alterations of behavior, masking, TTS, PTS, physiological injury and even death. All of these effects could induce stress, including mere audibility (Erbe, 2013).

Despite the observed impacts on cetaceans, the mechanism behind the effect of noise is still poorly understood which is highlighted by the amount of literature not finding an apparent effect (e.g. Nowacek et al., 2004; Croll et al., 2001). On the other hand, cetaceans could suffer from indirect effects of noise, e.g. boats may reduce or increase foraging success by affecting fish behaviour or deter predation by affecting the behaviour of large sharks (Mann, 2000).

Even if responses to anthropogenic noise are found, their biological significance on population-level (survival, birth rate, mortality) is extremely difficult to determine (Weilgart, 2007*b*; Bejder et al., 2006; NRC, 2005). The context in which an animal is exposed to sound is assumed to play an important role, including the demographic status of the animal receiving the sound, its population system and ecosystem changes, the characteristics, location, and movement of the sound source as well as the animal's location and behavioural state (NRC, 2005). Additionally, the history of the animal may also be a significant factor, as prior exposure to sound could have caused habituation or sensitization (NRC, 2005). Furthermore, acoustic stressors can add synergistically to other non-acoustic stressors such as chemical pollution and food depletion (Erbe, 2013).

The *Population Consequences of Acoustic Disturbance* (PCAD, Fig. 8) and *Population Consequences of Disturbance* (PCOD) models try to link noise characteristics to population effects. The aim of these models is to determine the consequences for a population by tracing acoustic disturbance though the life history of a marine mammal (NRC, 2005). Four transfer functions are used to relate different acoustic stimuli first to behavioural responses, then to effects on the critical life functions (e.g. breeding, feeding) which are linked to vital rates of an individual (survival, maturation, reproduction) to finally transfer individual changes to population effects (e.g. population growth rate, extinction probability). However, current data does not allow the PCAD model to operate as more than a conceptual model (NRC, 2005).

A link between exposure to sound and adverse effects on a population has not been documented conclusively (NCR, 2005). Nevertheless, noise from vessel traffic has been identified as one potential factor for a population decline in at least one cetacean population, the Southern Resident killer whales in the Western Pacific which have been listed under the Endangered Species Act (ESA) since 2005 (Lusseau et al., 2009; MMC, 2007).

All in all, there are still large gaps in our knowledge on the behavioural responses of cetaceans to anthropogenic ocean noise, and it remains unknown what levels of exposure are safe and how serious the potential effects of existing noise sources might be (NRC, 2005). However, ocean noise has potentially significant cumulative effects on marine mammals and other marine life (MMC, 2007). The National Research Council (2005) concluded that the effects that have been observed so far may be just the “tip of the iceberg”, and predicted that as the human population continues to grow, so will ocean-related human activities.

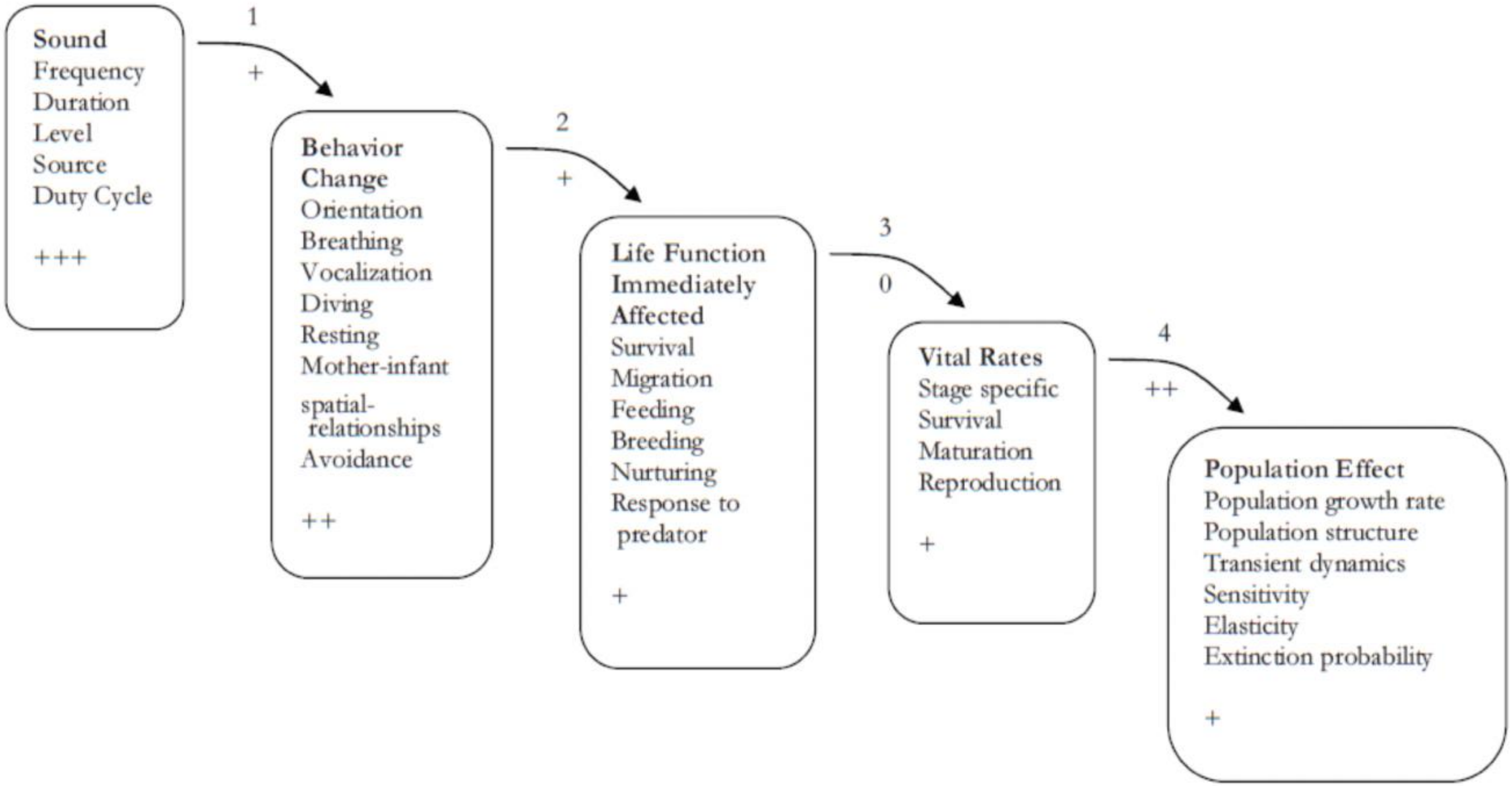


Fig. 8: The five stages of the Population Consequences of Acoustic Disturbance model (PCAD; NRC, 2005) that are required to relate acoustic disturbance to effects on a marine mammal population. The "+" signs indicate how well the variables in each box can be measured. The indicators between the boxes show how well the transfer function is understood, and range from "+++" (well known and easily observed) to "0" (unknown).

2.5.1. Temporary and permanent threshold shift

The threshold of audibility is the lower or upper level at which a sound is detectable, depending on the listener and frequency (Richardson et al., 1995). Threshold shifts represent actual changes in an animal's ability to hear (Nowacek et al., 2007). When mammalian auditory system is exposed to a high level of sound for a specific duration, the hair cells in the cochlear begin to fatigue. As they do not restore to their normal shape, the hearing sensitivity is decreased and only sounds louder than a certain level will be perceived. If the sound exposure is below a particular energy flux density limit, the hair cells will eventually return to their normal shape so that the hearing sensitivity is restored (temporary threshold shift, TTS). If the critical limit is exceeded, however, the hair cells in the cochlear become permanently damaged and die resulting in a permanent hearing loss (permanent threshold shift, PTS; Au & Hastings, 2008; Ketten, 2002). The risk of a threshold shift depends on the intensity, frequency of and the sensitivity to a specific sound. In general, the higher the sound pressure level and the longer the sound duration, the higher is the risk of a threshold shift (MMC, 2007).

TTS experiments with two species of odontocetes indicate that the cetacean auditory system is susceptible to threshold shifts as any mammal auditory system (Nachtigall et al., 2003; Finneran et al., 2000; Schlund et al., 2000). The severity of hearing loss from a particular signal might differ among species. Because hearing sensitivity depends on the species, it is impossible to say what decibel level is safe for all species for all signals (Ketten, 2002).

The cetacean auditory system is designed to transfer sound energy efficiently into the ear, so that hearing sensitivity is affected typically at much lower noise levels than those needed to damage other tissue (Whitehead et al., 2000). Noise-related trauma can even have lethal impacts. In 1992, two humpback whales died in Trinity Bay, Newfoundland, after their inner ears were damaged. Apparently, the injury was caused by exposure to underwater blasts at a construction site (Ketten et al., 1993). Even though explosions are the most obvious acoustic stimuli, they generally affect only a few individuals at a time (Whitehead et al., 2000).

2.5.2 Acoustic masking

Acoustic masking occurs when an extraneous signal covers a desired signal which consequently cannot be effectively perceived, recognized, or decoded (Clark et al., 2009; Nowacek et al., 2007). Masking of baleen whale vocalizations by human generated sound is likely for many species (NRC, 1995). It can interfere with intraspecific communication, predator and prey detection, and orientation, and, therefore, has the potential to affect critical life-history events (Nowacek et al., 2007; NRC, 2005, 2003). It has been suggested, for example, that the increase in ambient noise levels due to shipping impacts the ability of low-frequency fin whale calls to be heard at long range (Payne & Webb, 1971). The magnitude of the impact is difficult to determine until more is known about the components of vocalizations that are critical for baleen whales to hear (Edds-Walton, 1997).

2.5.3 Behavioural responses

A major concern is the impact of noise on the behaviour of cetaceans. Effects include changes in vocalizations, respiration, swim speed, diving and foraging behaviour, displacement, avoidance, and shifts in migration path (for reviews see Nowacek et al., 2007; Southall et al., 2007; Weilgart, 2007*b*).

Avoidance reactions are the most obvious indication of disturbance, and can be weak or strong. While some animals may swim directly away from a noise source at high speed, others may show only a tendency to swim away at a virtually normal speed (Richardson et al., 1995).

Migrating gray whales slowed down and altered course at ranges of 1-3 km when exposed to low-frequency sounds associated with offshore oil industry. Half of the >3500 whales observed avoided exposure to continuous stimuli at levels >117-123 dB, and to airgun pulses at levels >170 dB (Tyack, 1993). On their summering grounds in Alaska, humpback whales were reported to change orientation and move directly away from vessels within several kilometres (Baker & Herman, 1989). In response to mid-frequency (1-10 kHz) sounds, blue whales in feeding area changed their behaviour significantly (Goldbogen et al., 2013), including cessation of feeding, increased swimming speed and traveling away from the sound source. Responses seemed to depend on behavioural state, type of sound and received sound level (Goldbogen et al., 2013).

Christiansen et al. (2013*a*) reported the disruption of feeding behaviour of Common minke whales in the presence of whale-watching boats; in an earlier study, they showed an increase in the respiration rates when followed by boats, indicating a stress response, and an increased swimming speed (Christiansen et al., 2014). Both reactions resulted in increased energy expenditure (Christiansen et al., 2014), while the disruption of feeding behaviour lead to a decreased energy acquisition (Christiansen et al., 2013*b*). Like most mysticetes, Common minke whales are capital breeders. A decline in feeding success on the feeding grounds due to disturbance could result in decreased energy reserves for reproduction and nursing on the breeding grounds (Christiansen et al., 2013*a*).

Generally, behavioural reactions to noise are assumed to be transient and having the least severe impact on cetaceans (Southall et al., 2007); however, noise has the potential to cause animals to avoid certain areas, effectively reducing or degrading their habitat (Whitehead et al., 2000). Displacement from critical habitat over a period for up to ten years due to anthropogenic sound has been documented in gray whales and in killer whales (Morton & Symonds, 2002; Bryant et al., 1984). Nevertheless, changes in behaviour in cetaceans that lead to a decline in foraging efficiency, displacement, decrease in reproduction, increase in infant mortality etc., are usually difficult to demonstrate in their natural environment (NRC, 2005).

2.6 Benefits of thermal imaging based whale detection

Even though the temperature difference between skin surface and water has to be small in order to prevent heat loss (Irving, 1972), a whale's blow can be seen with high contrast in a thermal image. Blows of baleen whales are several meters high (e.g. 10-12 m for blue whales, Sears & Perrin, 2009) which allows detection of whales in a distance of up to 8 km (Zitterbart et al., 2013). Depending on the distance, other behaviours such as breaching and fluke-ups can also be detected in the thermal images. However, species identification is impossible.

Infrared(IR)-based whale detection offers many advantages to detect marine mammals over other detection methods. In order to minimize negative impacts from anthropogenic noise on marine animals, many environmental agencies have established guidelines for mitigation measures that are to be followed during seismic surveys, naval exercises, and pile-driving (Erbe, 2013; Dolman et al., 2009; Weir & Dolman, 2007). Visual monitoring is the primary (and often sole) method of animal detection, i. e. dedicated visual observers (Marine Mammal Observers, MMOs) monitor the ship's environ for the presence of marine mammals and arrange a shutdown of the sound source if an animal is detected inside a safety zone (Dolman et al., 2009; Weir & Dolman, 2007). However, as described in 1.2, activities like seismic surveys are often conducted continuously for weeks to months. Human observers have a limited ability to focus and a limited field of view, and visual observations are not only personnel-intensive but also impossible during night-time. Passive acoustic monitoring (passively listening for vocalizations of marine mammals) is very limited for species that are largely non-vocal or not vocalizing at the time of mitigation (Dolman et al., 2009; Weir & Dolman, 2007). In contrast, infrared-based whale detection offers the possibility to detect whales round-the-clock, including night-time, with a 360°-view (Zitterbart et al., 2013).

3. Material and methods

3.1 Infrared camera system

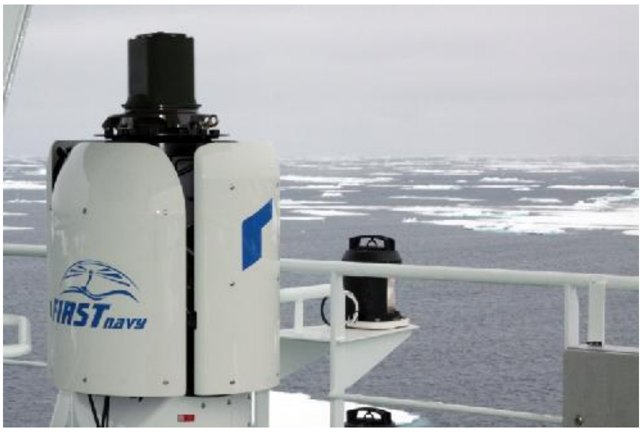


Fig. 9: Thermal imaging device „FIRST-Navy“ installed on *RV Polarstern* (© AWI).

The infrared camera system consists of a thermal imaging device (FIRST-Navy) which is mounted on an actively stabilized Gimbal (both Rheinmetall Defence Electronics, Germany) on the crow’s nest of *RV Polarstern* 28.5 m above sea level (Fig. 9). The cryogenic sensor is cooled to 84 K with a Sterling cooler and has a thermal resolution better than 0.08 K. The optics of the camera were at 29.5 m above sea level. Scanning 360° horizontal x 18° vertical at 5 revolutions per second, the sensor provides a 5-Hz video stream in the 8-12 µm band (long wave infrared) of the thermal field of the ship’s surroundings. Thereby, a radius beyond 110 m from the ship’s bow to the horizon is covered at horizontal and vertical resolutions of 0.05°/pixel and 0.03°/pixel, respectively (Zitterbart, 2013; Zitterbart et al., 2013). However, due to the crow’s nest in the back of the camera the usable observation angle was 290° (146° to starboard and 144° to port).

3.2 *RV Polarstern*

Fig. 10: *RV Polarstern* on her way to Neumayer station III on expedition ANT-29.2 in 2012 (© F. Mehrtens / AWI).

RV Polarstern (*PS*, Fig. 10) is a research and supply vessel designed as an icebreaker (German ice class ARC3). It is owned by the German Federal Republic and operated by AWI. She is used for research as well as for supply of the German research station in Antarctica (Neumayer station III). In addition, she is equipped with a meteorological observatory continuously collecting data on air temperature and relative humidity, wind speed and wind direction, precipitation, visibility etc. Two thermosalinographs (type SBE21 SEACAT, Sea-Bird electronics, USA) provide quasi-continuous information about water temperature, salinity, and sound velocities.

As a double-hulled icebreaker with an overall length of 117.91 m and a beam of 25.07 m, *Polarstern* is operational at temperatures as low as -50 °C and can break through 1.5 m thick ice at a speed of approximately 5 kn (ca. 9.25 km/h). Ramming can break ice at least 2 m thick. *Polarstern* can reach a speed up to ca 16 kn (ca. 29.6 km/h). The four main diesel engines (Model RBV M 540, Klöckner-Humboldt-Deutz-AG, Germany) have a total power of 14116 kW (19192 PS). She is equipped with two controllable pitch propellers with a revolution of 180 min^{-1} with four wings made of stainless steel. The maximum draught is 11.2 meters with a displacement of 17300 tons. Lightweight tonnage is 11904 tons (Albert et al., 1983). Since her commissioning in December 1982, *Polarstern* has completed more than 50 expeditions in the Arctic and Antarctic and spends almost 310 days at sea each year (for a list of expeditions see http://expedition.awi.de/expeditions).

3.2.1 Sound profile of RV Polarstern

In order to assess the sound levels typically received by a whale when passed by *Polarstern*, two measurements of *Polarstern*'s sound profile were conducted in the Southern Atlantic Ocean on 12 and 13 December, 2014 during expedition ANT-30.2 (alias PS89) by Olaf Boebel and Karolin Thomisch, members of the Ocean Acoustics Lab at AWI. .

Each time a passive acoustic hydrophone was submerged at shallow depth from a zodiac and received levels were measured while *Polarstern* passed the zodiac and the hydrophone (Fig. 11). The zodiac departed to some distance from *PS* where its engines were stopped. A passive acoustic hydrophone (ICListen, OceanSonics, Canada) was attached to a rope by cable ties and submerged to approx. 5 and 10 m depth, respectively, using an anchor weight of 7.5 kg. The hydrophone recorded continuously at 512 kHz, 24 bit. After launch of the zodiac, PS resumed cruising speed (ca. 10 kn) and passed the zodiac and the hydrophone with the point of closest approach being ca. 0.1 nm (ca. 185 m).

The measurements were conducted at 56° 55,32' S, 0° 0,86' E (12 December 2014) and at 59° 2,50' S, 0° 6,33' E (13 December 2014). Sound profiles, i.e. the period during which *PS* passed by the hydrophone, lasted for 8 and 7 min, respectively (Tab. 4). Start and end times were obtained from the station book records of *RV Polarstern* via DAVIS-Ship ("DShip" by WERUM Software & Systems, a software for data acquisition and management of ship-based nautical and scientific measuring systems and devices).

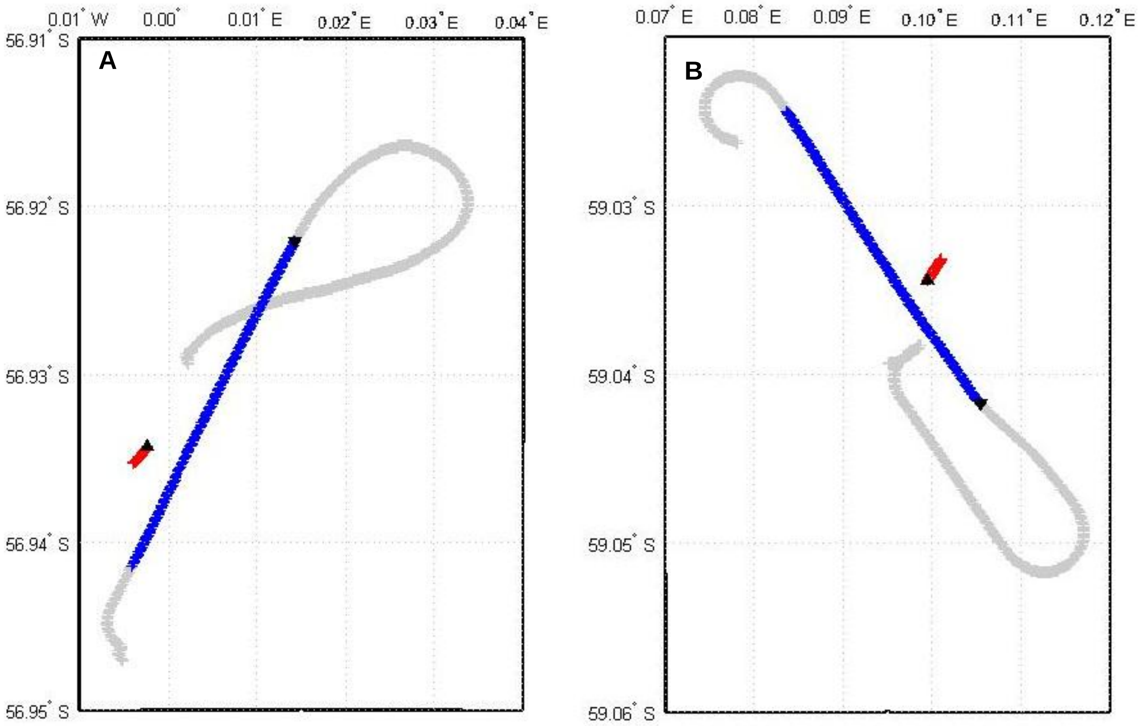


Fig. 11: Sound field measurements of *RV Polarstern* at two different positions on 12 (A) and 13 (B) December, 2014 in the Southern Atlantic Ocean. In each case, red symbol indicates a zodiac with a submerged hydrophone lowered to 5 and 10 m, respectively. Gray and blue line marks the track of *Polarstern* with the blue part indicating the part of the track during which the hydrophone recorded the noise levels generated by *Polarstern* passing by with the point of closest approach being ca. 0.1 nm (ca. 185 m).

Geographic positions and heading of *PS* during the sound profile measurements were downloaded from DAVIS-Ship with a temporal resolution of 1 s. Geographic positions of *Polarstern* were recorded midship, representing the position of the scientific navigation platform MINS (serving as reference location on *RV Polarstern*). Geographic positions of the hydrophone were recorded every 10 s with a GPS device (GPSmap 62stc, Garmin) located on the zodiac. Potential drift of the hydrophone due to currents was considered negligible. Direct comparability of the positions of *PS* and the hydrophone were obtained by interpolating the hydrophone's GPS position at 1 s resolution. Distances between *PS*'s and the hydrophone's position as well as angles between the *PS*'s track and the hydrophone's position were calculated with a resolution of 1 s.

The acoustic recordings were highpass-filtered with a pass frequency of 40 Hz (Butterworth filter) to prevent low-frequency noise originating from wave action influencing the analysis. Amplitudes of the received sound levels (SPL_{rms}) were calculated temporally overlapping in two-

Tab. 4: Acoustic measurements of *RV Polarstern* sound emissions during ANT-30.2 (alias PS89).

Date	Station ID	Latitude	Longitude	Profile start (UTC)	Profile end (UTC)
12.12.2014	PS89 017-1	56° 55,32’ S	0° 0,86’ E	10:33	10:41
13.12.2014	PS89 020-4	59° 2,50’ S	0° 6,33’ E	13:45	13:52

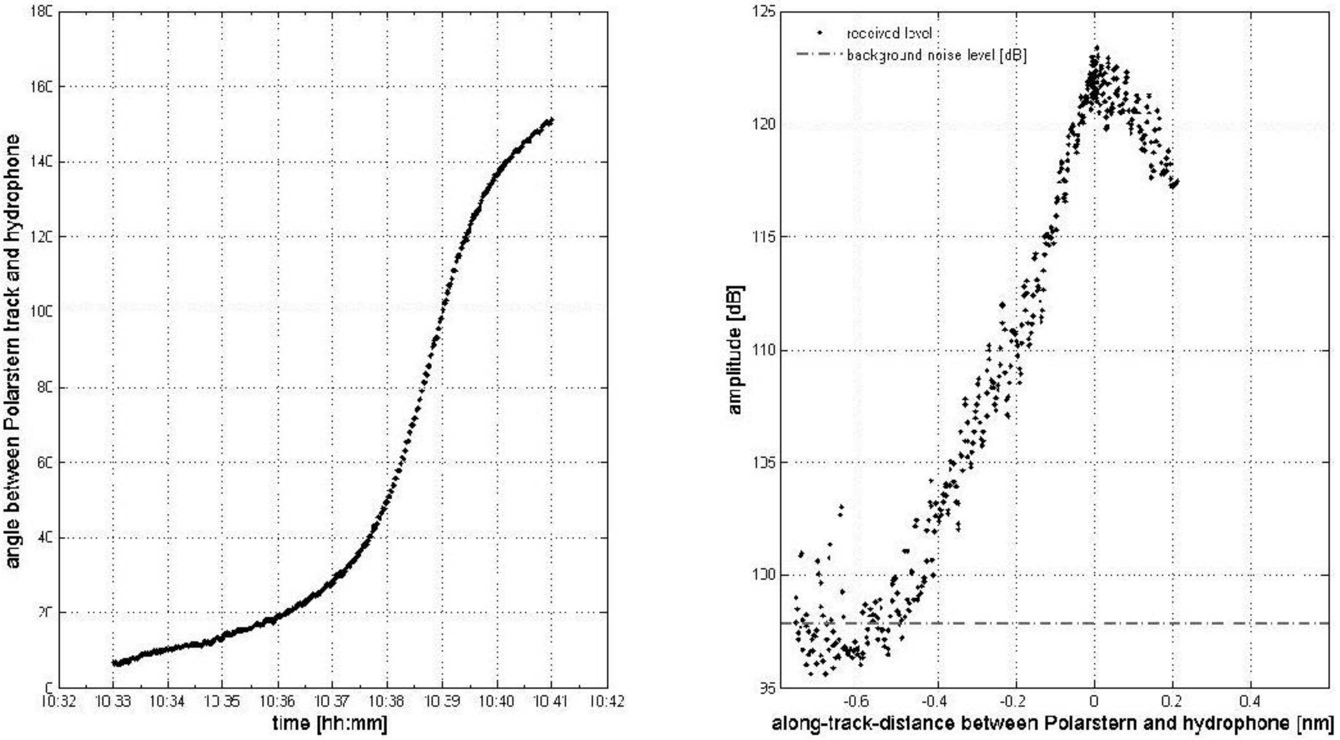
second intervals every second over the entire frequency range (i.e. 40 – 256,000 Hz). Ambient noise levels representative for the acoustic environment conditions during the sound profiles at each of the two days were calculated as SPL_{rms} over the entire frequency range from 3-5 min before the start time of the sound profile.

Received sound levels were correlated with distance between the positions of *PS* and hydrophone as well as with the angle between *PS*’s track and the hydrophone’s position at each time step.

The two measurements of *Polarstern*’s sound field revealed received levels ranging from 95 to a maximum of 124 dB depending on both the angle and the distance between the ship and the hydrophone (Fig. 12, 13). During the first measurement, the background noise level was approx. 98 dB and approx. 102 dB during the second measurement.

Right ahead of *Polarstern*’s path the received level was lowest (95 dB). Depending on the background noise level, the ship’s noise is not audible in the sector in front of it. At a background noise level at ~103 dB, the ship’s noise could not be heard from 0° to ~15° to the ship’s side. At greater angles, the received level exceeded the background level, and increased from ~102 dB to ~120 dB at an angle of 45-50° when *PS* approached the hydrophone. The range from ca. 30-45° is the ship’s shadow zone in which the received level of the ship’s noise is lower than expected since the sound rays from the propeller are reflected by the ship’s stern. While *PS* passed by the hydrophone and the angle increased from 50 to 150°, the received level stayed rather constant ranging from 120 to 124 dB. The received levels were highest when the along-track-distance between *PS* and hydrophone was about 0 nm. Along-track-distance does not refer to the actual distance, but along-track-distance of 0 m, for example, means that *PS* and the zodiac with the hydrophone were at the same level and the zodiac was at an angle of 90° to *PS*. As *PS* passed by the hydrophone and moved away, the received noise level decreased at angles larger than 150°. When the angle between the hydrophone and *PS* was approx. 170°, the received noise level was measured at 108 dB. The increase of the received noise level during *PS*’s approach happened faster than its decline when *PS* moved away.

A


angle between Polarstern track and hydrophone
time [hh:mm]
0
20
40
60
80
100
120
140
160
180
10:32
10:33
10:34
10:35
10:36
10:37
10:38
10:39
10:40
10:41
10:42
received level
background noise level [dB]
amplitude [dB]
along-track-distance between Polarstern and hydrophone [nm]
95
100
105
110
115
120
125
-0.6
-0.4
-0.2
0
0.2
0.4

B

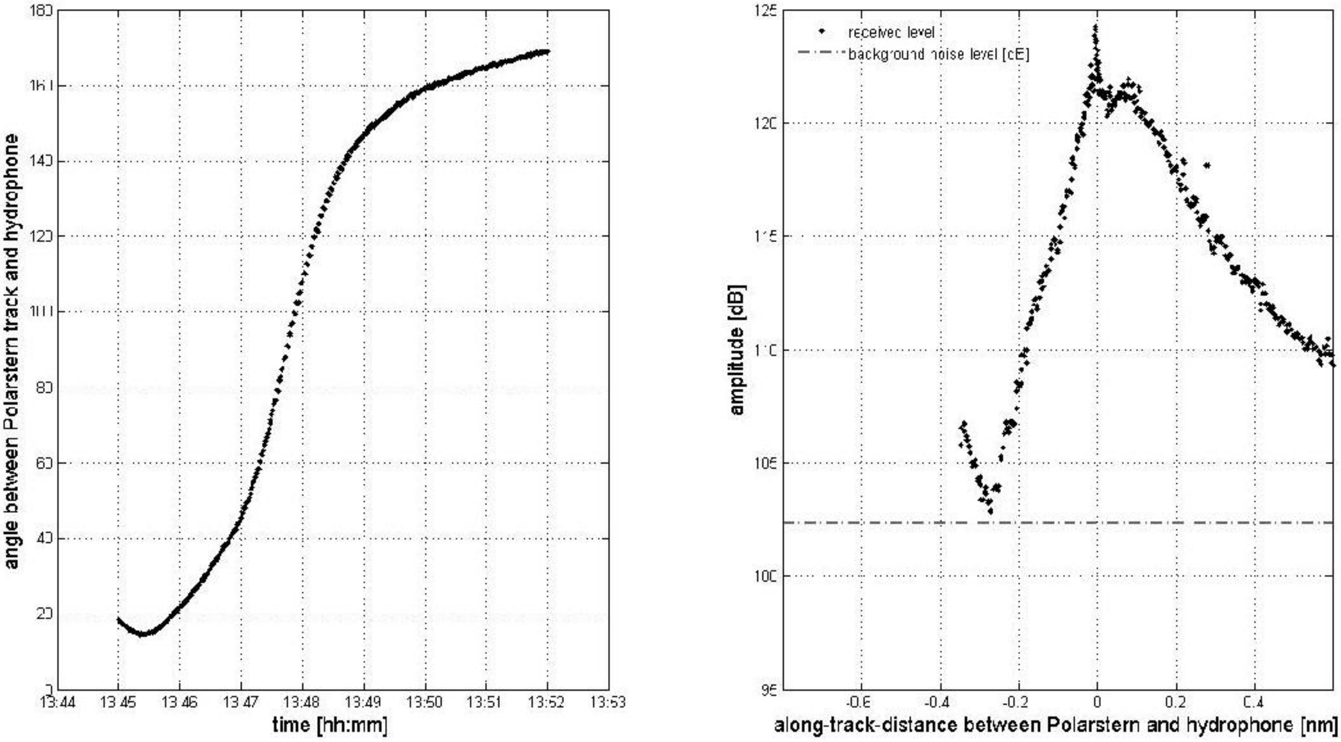

angle between Polarstern track and hydrophone
time [hh:mm]
0
20
40
60
80
100
120
140
160
180
13:44
13:45
13:46
13:47
13:48
13:49
13:50
13:51
13:52
13:53
received level
background noise level [dB]
amplitude [dB]
along-track-distance between Polarstern and hydrophone [nm]
95
100
105
110
115
120
125
-0.6
-0.4
-0.2
0
0.2
0.4

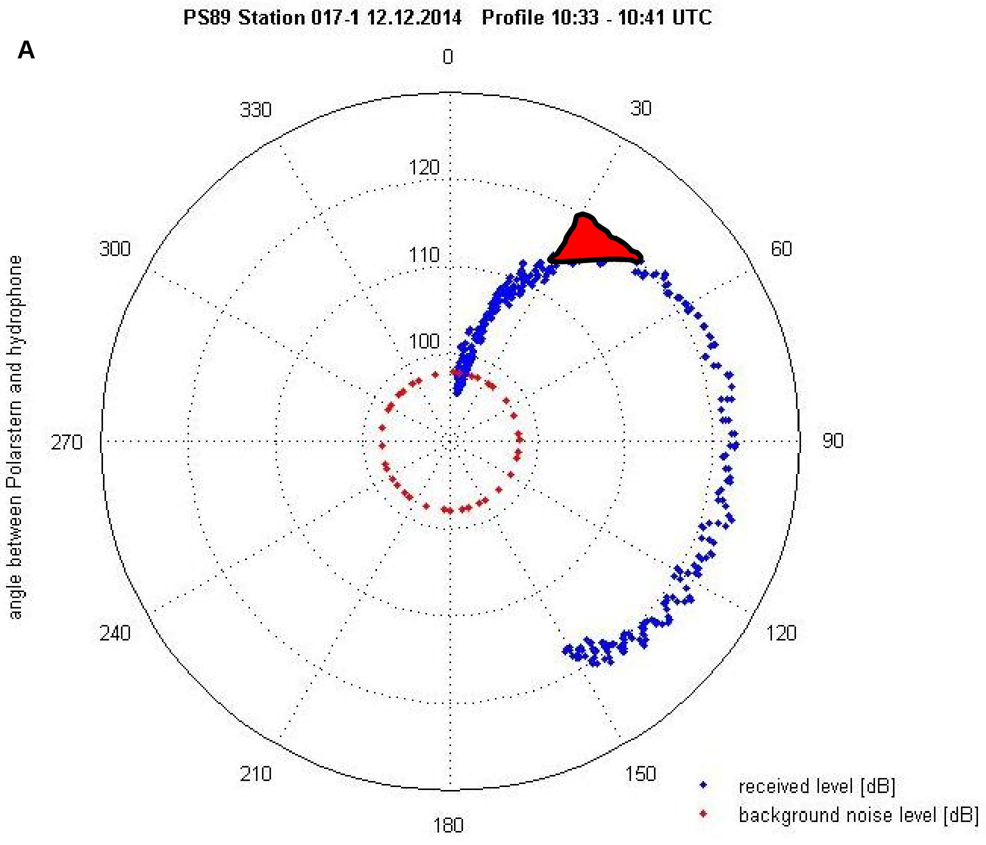
Fig. 12 (previous page): Change of the angle between *Polarstern* and the hydrophone in degrees (left) and the amplitude of the background noise and the received level (dB; right) during the sound profile measurement on 12 (A) and 13 (B) December, 2014 at two different positions in the Southern Atlantic Ocean.

A Left: As *PS* approached the hydrophone, passed by it and then moved away (see Fig. 10 A), the angle increased from ~5° in the beginning of the measurement to ~150°.

Right: Amplitude of received levels [dB] from *PS* measured by the hydrophone versus the along-track-distance between ship and hydrophone [nm]. When *PS* approached the hydrophone from an along-track-distance of ca. 0.6 nm (1110 m), first the amplitude of the received level was lower than the background noise of ~98 dB. From a distance of ca. 0.5 nm (920 m), the received level exceeded the background noise and increased linearly to a peak of ~124 dB when *PS* and the hydrophone were at the same level (along-track-distance of 0 m). Then, the received level declined with increasing distance.

B Left: From the beginning to the end of the sound profile measurement, the angle between *PS* and the hydrophone increased from ~15° to ~170°.

Right: Amplitude of received levels [dB] from *PS* measured by the hydrophone versus the along-track-distance between ship and hydrophone [nm]. While *PS* was approaching from a distance of ~0.25 nm (460 m), the amplitude increased linearly to a peak of approx. 124 dB when the along-track-distance between ship and hydrophone was 0 nm. As the distance increased, the amplitude first declined to ~121 dB, and increased again to almost 122 dB, before decreasing constantly to ~110 dB at a distance of ca. 0.6 nm (1110 m). During the measurement, the background noise remained at a constant level of ~102 dB.



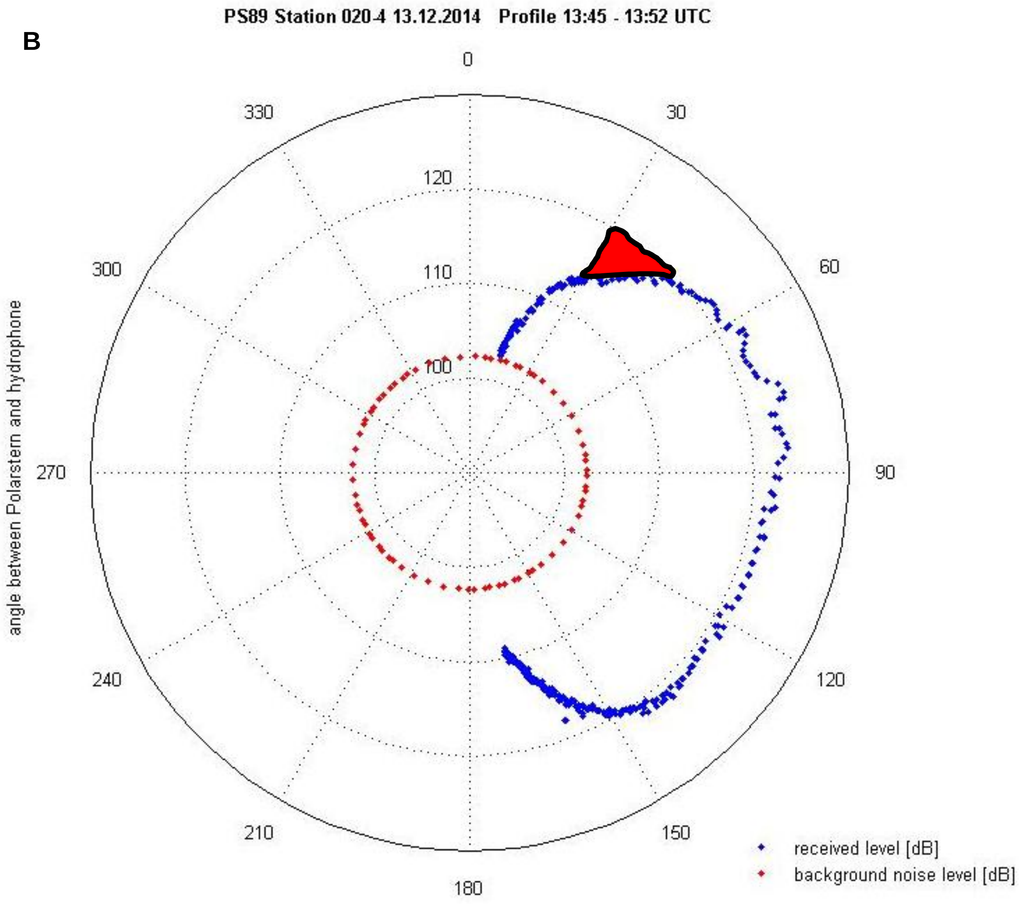


Fig. 13: Sound profile of *RV Polarstern* measured at two different positions in the South Atlantic Ocean on 12 (A) and 13 (B) December, 2014. The background noise level and the received level of the noise generated by *PS* are plotted in relation to the ship's position.

In each case, *PS*'s position is in the center of the dashed concentric circles indicating sound levels from 90 to 130 dB. Dashed lines running from the center to the outermost circle indicate the angle between *PS* and the hydrophone (clockwise with 0° being directly ahead of the ship's path). Red dots mark measurements of the background noise level all around *PS*'s position. Blue dots mark measurements of the noise generated by *PS* recorded with a hydrophone as the ship was passing by it. Red triangles mark the range of angles from ca. 30° to 45° (*PS*'s shadow zone) in which the received levels were lower than expected due to acoustical shadowing.

Considered together, the two sound profiles indicate the received levels from the ship's noise in angles ranging from ~0° to ~170°. Right ahead of the ship, the received level was lowest and exceeded by the background noise level. When the background level was ~103 dB, the received level exceeded it at an angle of approx. 15° (B). As *PS* approached the hydrophone, the angle to the hydrophone became larger and the received level increased up until an angle of 45-50°. At this angle, the received level was approx. 120 dB and remained rather constant up to an angle of approx. 150° (A, B). As *PS* moved away from the hydrophone, the distance to the hydrophone increased and the

3.3 Data collection

Data were collected with the IR camera system between 05:35 and 20:02 UTC on December 7, 2012, during the 50-day long expedition ANT-29.2 (alias PS81) to the Atlantic sector of the Southern Ocean, starting in Cape Town, South Africa, and ending in Punta Arenas, Argentina (Fig. 14). Data collection was conducted in the South Atlantic Ocean between 53.95° to 54.65° S latitude and 6.96° to 2.31° E longitude covering a distance of 275.00 km. Throughout the data collection *Polarstern* was underway with a speed ranging from 4.31 kn (ca. 7.98 km/h) to 12.30 kn (ca. 22.78km/h) and a mean speed of 9.58 kn (ca. 17.74 km/h). The average depth in the study area about 2000 m with a minimum depth of ca. 190 m, and a maximum depth of 3960 m; the water temperature was between -0.5 and -0.1 °C. During the different ship-whale encounters

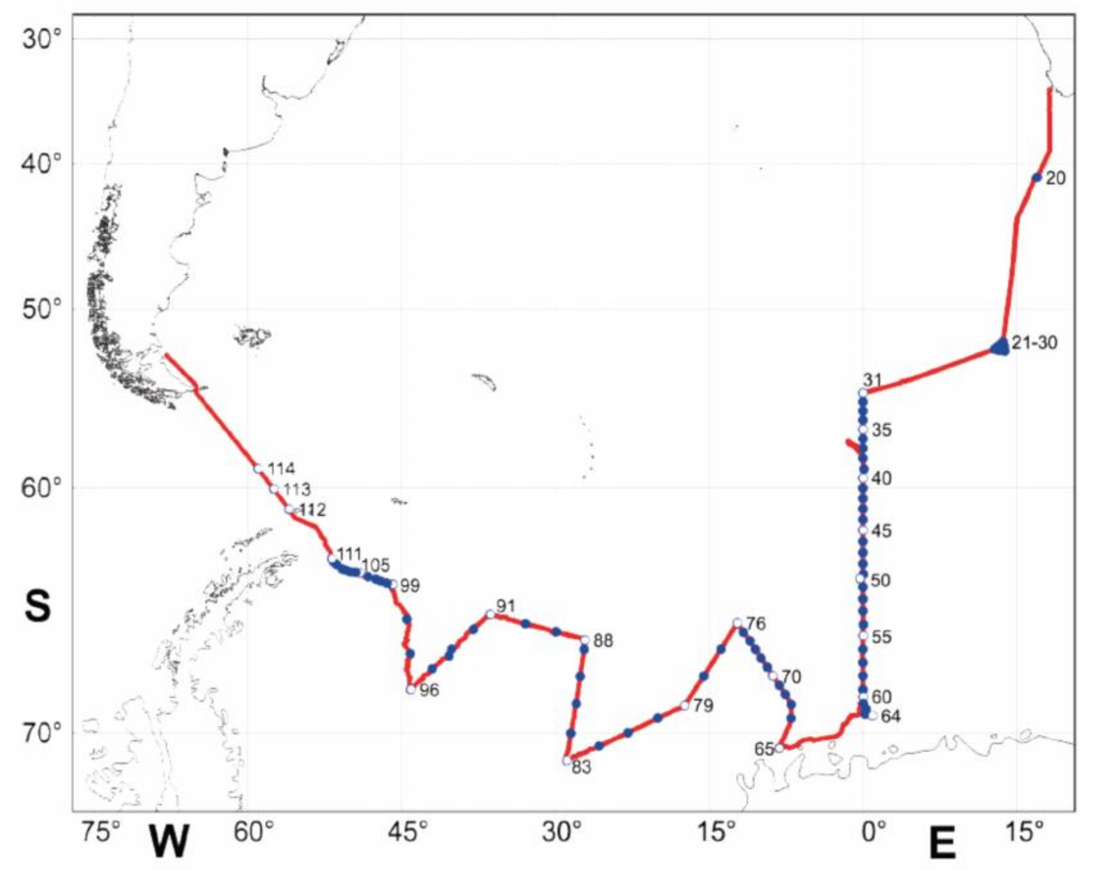


Fig. 14: Chart of the cruise track of the expedition ANT-29.2 (red line) to the Antarctic which started in Cape Town, South Africa, and ended in Punta Arenas, Argentina (Boebel, 2013).

recorded during this time, the mean wind speed ranged from a minimum of 13 kn (4 Bf) to a maximum of 24 kn (6 Bf; Tab. 5). The visibility was constantly above 10000 m.

Tab. 5: Mean wind speed [kn], [Bf] and mean visibility [m] during the different ship-whale encounters recorded during the observation time.

Encounter	Wind speed [kn]	Wind speed [Bf]	Visibility [m]
#1	24	6	16186
#2	22	6	17465
#3	19	5	17196
#4	21	6	18229
#5	17	5	16619
#6	17	5	17739
#7	12	4	21861
#8	21	5	20306
#9	14	4	19369
#10	14	4	19247
#11	13	4	21275
#12	13	4	20668
#13	13	4	20521
#14	15	4	20743
#15	15	5	20614
#16	16	5	20370

During the observation time, two MMOs recorded whale sightings from the ship's bridge using bare eyes and handheld binoculars (7x50; Fig. 15) and were on-effort for a total of 6 h. They recorded sighting time, distance to the whale (in steps of 0.25 reticule below the horizon), its bearing relative to the ship's position (in steps of 5°, 0° being the ship's heading), and, if possible, species and an estimation of the number of animals. The distance *r* of an event was calculated as follows: $r = \frac{platform\ height\ + observer's\ eye\ height}{number\ of\ reticules * 10} * 1000$.

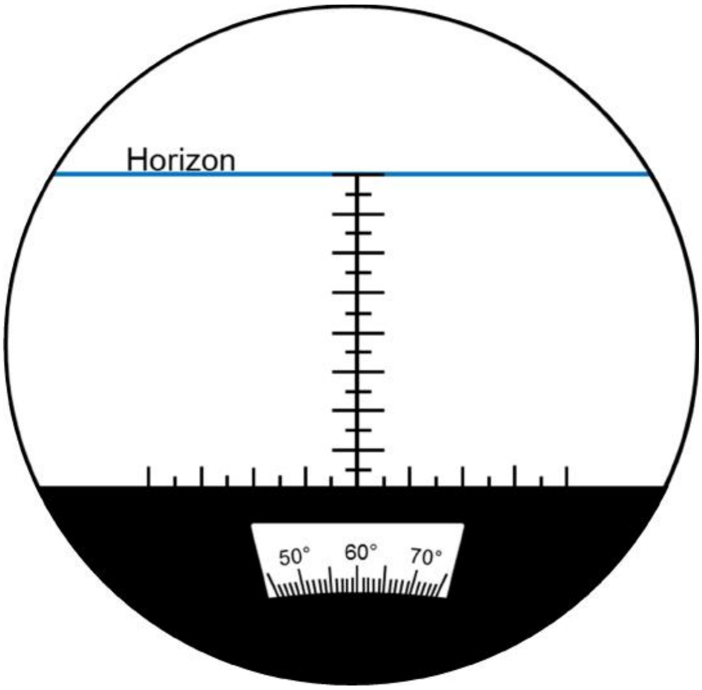
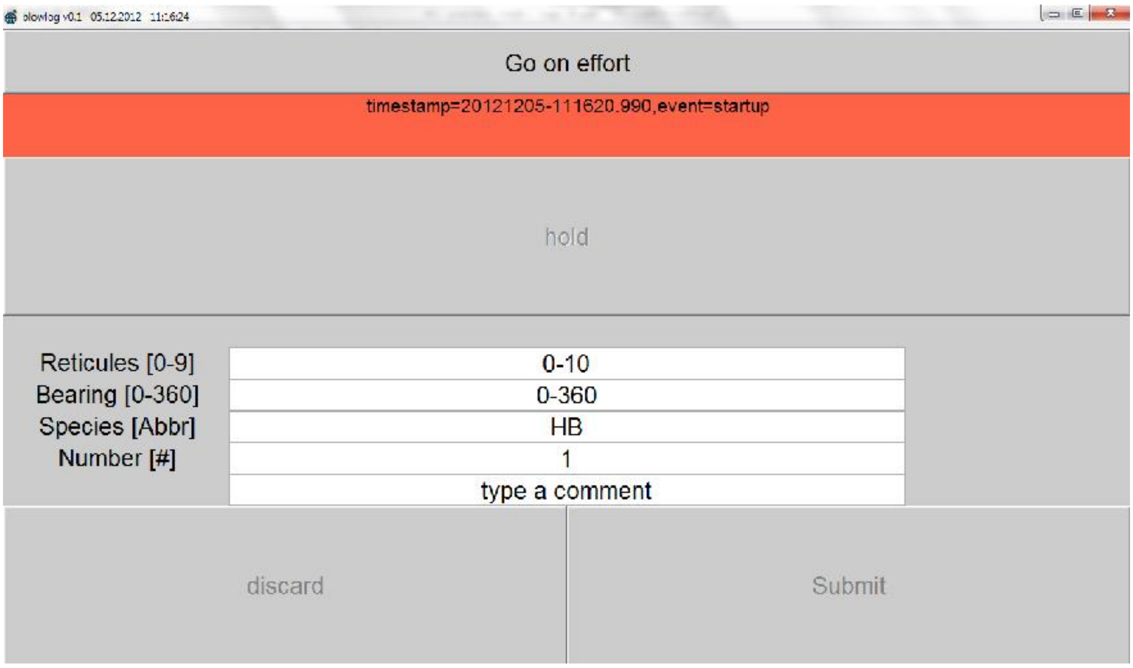


Fig. 15: Scheme of the perspective through binoculars. Knowing the observation platform's height, the distance of an object can be calculated by counting the reticules below the horizon. The bearing of an object can be derived from the compass display at the bottom.

These records were logged with the software “blowlog” (Fig. 16), and were the basis for the analysis by retrospective human screening of the correspondingly thermal video recordings.

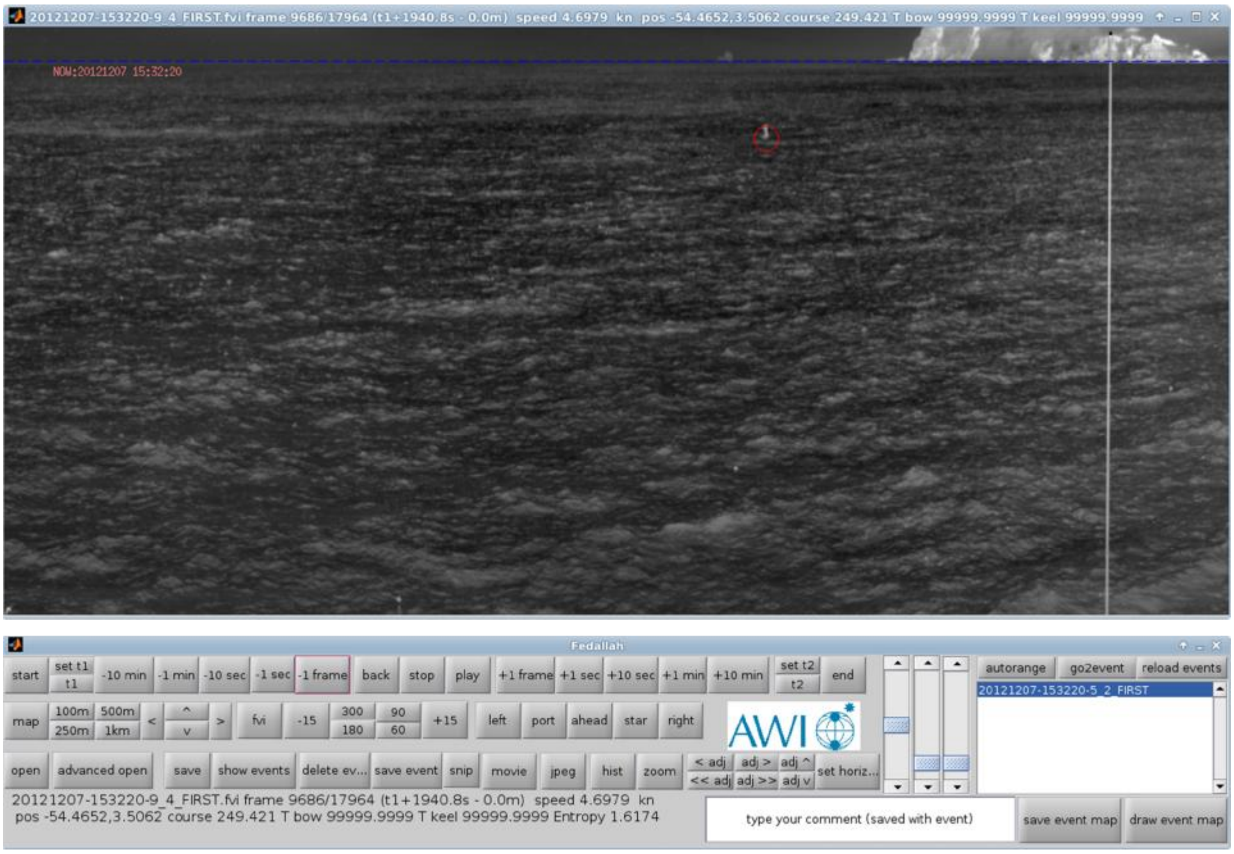


```
timestamp=20121205-111620.990,event=startup
```

Reticules [0-9]	0-10
Bearing [0-360]	0-360
Species [Abbr]	HB
Number [#]	1
	type a comment

Fig. 16: Screenshot of the user interface of the “blowlog” software which was used by the MMOs on the bridge of *RV Polarstern* to log an event. The parameters that have to be entered for a complete logging comprise the number of reticules below the horizon (given in steps of 0.25 reticule), the bearing relative to the ship (0° being in front of the ship), if possible, the species, and an estimation of the number of animals. Additionally, it is possible to add a comment. Before entering the parameters, the software saves the time of the entry automatically. This allows to precisely log the time of observation of a whale blow while additional data can be entered afterwards.

Retrospective analysis of the thermal video recordings was done using a software suite called “Fedallah” developed at the AWI (Fig. 17). This software allows screening and annotating of thermal imaging data as well as calculating distance and bearing of detected events which are used to determine its position relative to the position of the ship. The distance between ship and whale can be calculated by spherical triangulation (Lerczak & Hobbs, 1998) using ship height and the angle below the horizon (resolved to ± 0.05°), while the bearing is available to within 0.1°. The video stream was displayed on two screens with a resolution of 1920 x 1200 pixels each. For analysis of the pictures a segment of 180° or smaller (typically 90°) was chosen in order to display in a resolution equal or better than the original pictures. For each encounter, the thermal video stream was analysed from the time of the first visual detection ensuring that the MMOs were alerted.



```
20121207-153220-9_4_FIRST.fvi frame 9686/17964 (t1+1940.8s - 0.0m)  speed 4.6979  kn  pos -54.4652,3.5062 course 249.421 T bow 99999.9999 T keel 99999.9999
NOW:20121207 15:32:20
```

```
20121207-153220-9_4_FIRST.fvi frame 9686/17964 (t1+1940.8s - 0.0m)  speed 4.6979  kn
pos -54.4652,3.5062 course 249.421 T bow 99999.9999 T keel 99999.9999 Entropy 1.6174
```

```
20121207-153220-5_2_FIRST
```

Fig. 17: Top: Screenshot of a 60°-segment of the thermal video stream displayed in the software suite „Fedallah”. Red circle marks the blow of a humpback whale in a distance of 666.14 m at 22.4° at 15:32:20 UTC, December 7, 2012. Blue dashed line marks the horizon.
Bottom: Screenshot of the user interface of „Fedallah” which was used to detect events in the thermal video recordings. It allows the user to manage the recordings and save detected events. It also provides information about the events, i. e. distance and bearing relative to the ship, and the ship's navigational data, i. e. GPS position, course, and speed.

Fig. 18 illustrates the estimated error (absolute and relative) in the distance calculation for both the thermal image and MMOs. It is assumed that the vertical position of an event in the IR image is determined with an accuracy of ±1 pixel and ±0.125 reticule using binoculars. Spherical triangulation which is used for the distance calculation results in a distant-dependent error. For events with a distance of less than 5 km, the relative errors are within 12% (Zitterbart et al., 2013).

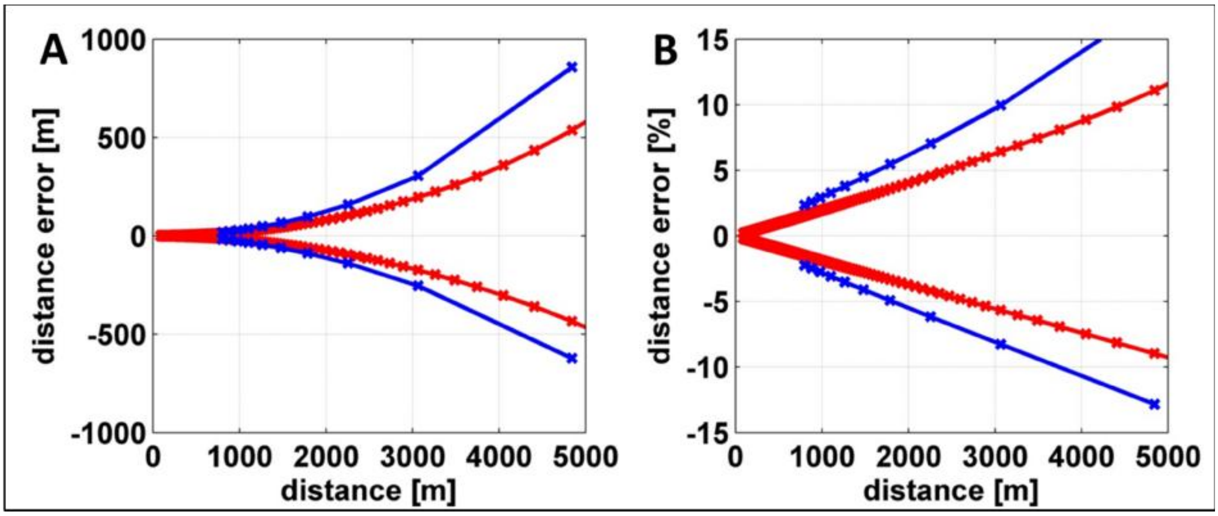


Fig. 18: Absolute (A) and relative (B) error estimation of distance calculation based on the thermal image and binoculars (Zitterbart et al., 2013). It is assumed that the vertical position of an event in the IR image is determined with an accuracy of ±1 pixel and with ±0.125 reticule accuracy using binoculars. Thus, the spherical triangulation used for the distance calculation results in a distant-dependent error. Red and blue colours indicate upper and lower boundaries, respectively. For events with a distance of less than 5 km, relative errors are within 12% (Zitterbart et al., 2013).

3.4 Data analysis

Using the information about the whale's distance and bearing in combination with the ship's navigational data, i. e. GPS positions and heading, detailed geo-referenced maps from each ship-whale encounter were derived. The maps were created and analysed using Geographic Information System software (ArcGIS 10.1; Esri Inc., USA).

For three encounters that were detected visually no corresponding thermal video recordings were available. One encounter was aborted because the visually detected event was outside the camera's usable observation angle. These four encounters were not taken into consideration.

3.4.1 Consolidation

The 360°-images provided by the infrared camera allow for retrospective observation of several pods at the same time without missing events which is hardly possible for MMOs. In order to determine which of the thermal imaging based events belonged to the focal pod, a pod of whales was defined as a group of animals in relatively close proximity and whose behaviour seemed to be linked, i. e. swimming in the same direction. Therefore, the following criteria were applied: Events occurring within 500 m of each other were considered belonging to the same pod or the same animal. Events that occurred between 500-900 m were considered to belong to the focal pod if their position could be reached with a speed of max. 11 m/s (39.6 km/h). This speed corresponds to the maximum speed that has been recorded for fin whales (40 km/h; Heckel & Schramm, 2005). If an event was further away than 900 m from any event of the focal pod, it was considered to belong to a different pod. In addition, events that occurred in a distance greater than 500 m from any event of the focal pod that had been detected until (or after) that time and could not have been reached from other events. An example of the consolidation is shown in Fig. 19.

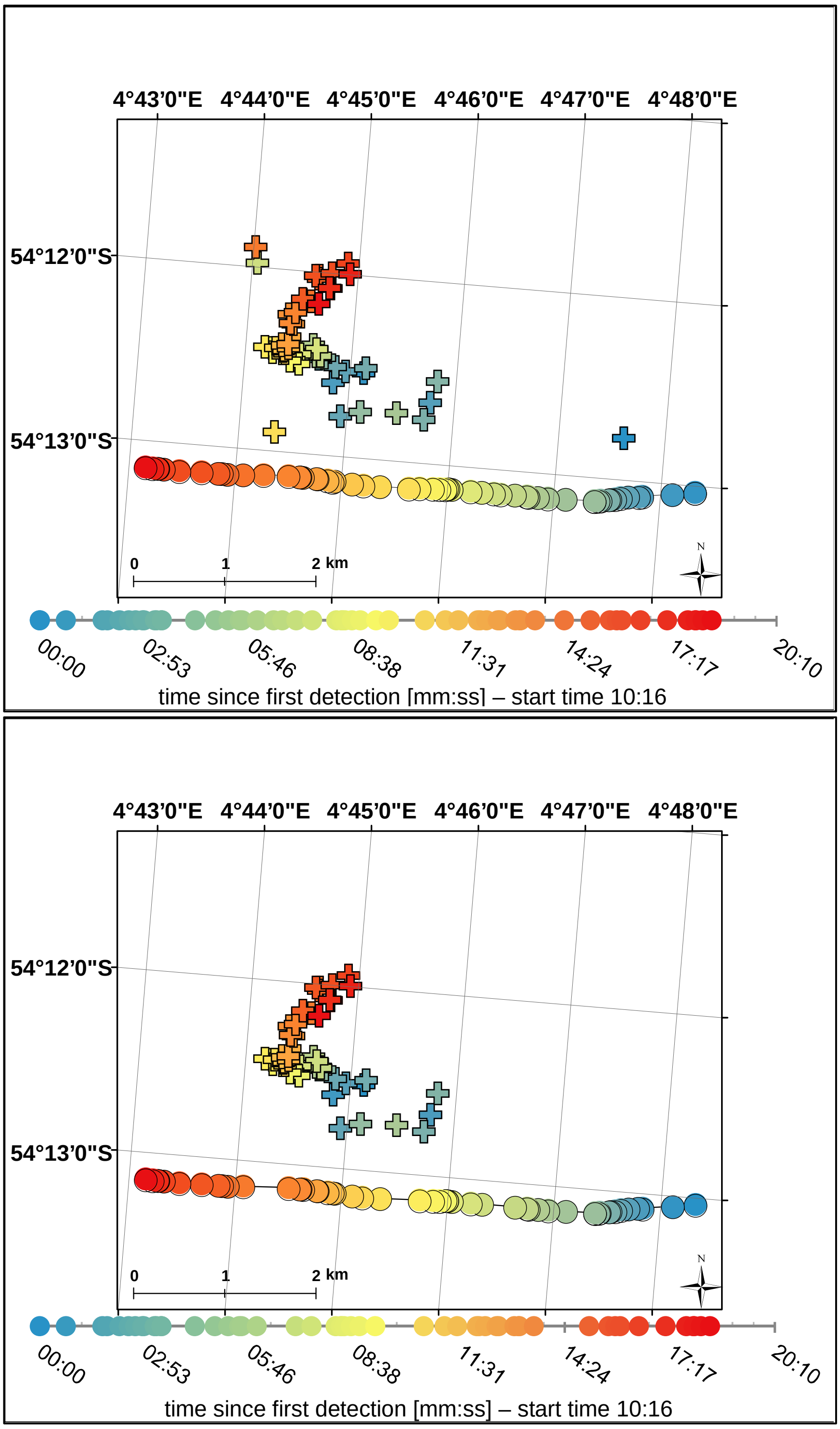


Fig. 19: Geo-referenced maps of ship-whale encounter #4 before (top) and after (bottom) the consolidation process. Coloured circles mark positions of *RV Polarstern* along her route, coloured crosses mark the track of a pod of fin whales. The colour represents time, i. e. circles and crosses with the same colour mark *Polarstern*'s position and a whale's position at the same time. As result of the consolidation process described above, five of the 56 events were deleted; one event was further away than 900 m, four events were between 500 and 900 m from the focal pod but could not be reached with a speed of max. 11 m/s. The remaining 51 events represent the track of the focal pod over a period of ca. 19 min.

3.4.2 Determination of a minimum number of whales in the focal pods

The number of animals in the focal pod was estimated based on the time between events and the swimming velocities. If an event occurred within five seconds before or after another event, they were considered to belong to different animals. Additionally, if the distance between two events could not have been travelled with a speed of 11 m/s or less, the two events were considered to belong to different animals.

3.4.3 Modelling of focal pod movement

To determine whether the focal pod showed a significant change in direction correlated random walk models were used. This allows to model different whale paths with the same motion statistics as they showed before the suggested behavioural change. For this the whale trajectory was separated into two parts divided by the last measured position p_0 before behavioural change. For focal pods that did not change their behaviour the position p_0 was chosen randomly in the second half of each trajectory. From the first path the distribution of step-sizes and turning angles between adjacent whale locations were obtained. Those distributions were used to model probable trajectories after p_0 by randomly choosing a new step-size and turning angle from the respective distributions and calculating a new position. A noise term of ± 10° and ± 30 m was added to avoid modelling equal paths which might arise if the trajectory of the whale used to determine motion statistics is very short. This was done for as many steps as observed after p_0 in the original data. This process was conducted independently for each encounter. Due to a very low number of observations during three encounters it was impossible to establish even remotely reliable motion statistics distributions. Therefore no correlated random walk models could be established for those encounters.

3.4.4 Focal pod movement

For every event of the focal pods, the angle and the distance between the whale's and *Polarstern*'s positon was calculated. Angles are given in a range from 0-180° no matter on what side of the vessel the pod was detected. For pods showing an obvious change in direction, the angle α between the paths before and after the change of the traveling direction was calculated (example in Fig. 20).

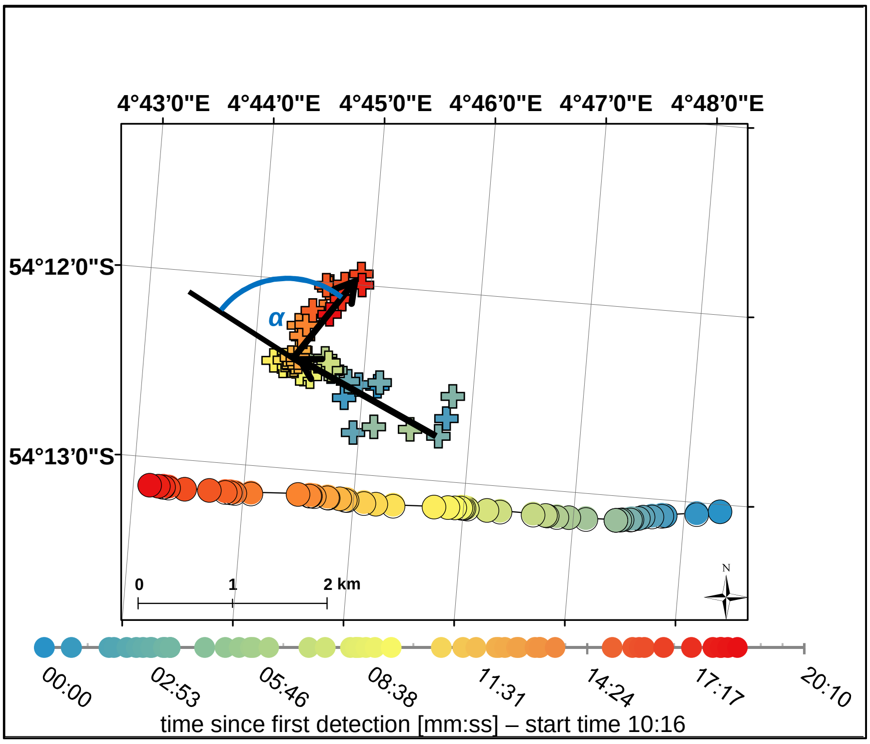


Fig. 20: Geo-referenced map of the movement of the focal pod of encounter #4. When focal pods obviously changed the direction of their movement (indicated by black arrows) during the encounter, the angle *α* between the paths before and after the change of the traveling direction was calculated.

3.4.5 Comparison of thermal imaging based and visual whale detection

In order to obtain a comprehensive comparison all detected events were taken into consideration regardless of the focal pod.

The number of detected events in each encounter and in total was compared. When multiple events occurred within one second, the observers could only record one. Therefore, all thermal imaging based events within that single second were counted as observed by the MMOs.

The comparison of the distance estimation was based on the distances calculated in GIS software for both the thermal imaging based and the visual detection. Only matching events were taken into consideration, i. e. visually detected events that were within ± 3 s and within ± 10° of a thermal imaging based detection ensuring that detections of the same event were compared. If a visually detected event could match several thermal imaging based detections with a difference in distance of >100 m, it was excluded from the analysis. If the difference in distance was <100 m, the event with the greater distance to *Polarstern* was matched with the visually detected event. The difference in distance estimation was analysed statistically with the

Wilcoxon matched-pairs signed rank test using GraphPad Prism 6 (GraphPad Software, Inc., USA).

Furthermore, the possibility to assess the behavioural response of a whale or a pod to the vessel by visual observation was investigated by the comparing geo-referenced maps of the ship-whale encounters that were based on the visual recordings and based on the thermal video stream for each encounter. For one encounter, no visual data was available due to lack of distance estimation by the MMOs. Hence, this encounter was excluded from the comparative analysis.

4. Results

Over a period of 14.5 hours a total of 20 ship-whale encounters were observed during 6 hours of observation. Of these 20 encounters, three encounters consisted of only 1-3 events making it impossible to evaluate the focal pods' behaviour. Hence, these three encounters were excluded from the analysis. The remaining 17 encounters consisted of 955 events comprising a great majority of 951 blows, 2 fluke-ups, and 2 breaches. Broken down by species, 6 (35%) encounters were with humpback whales, 5 (29%) were with fin whales, and during 2 (12%) encounters individuals of both species were observed. For four encounters (24%) species identification was impossible.

The 17 encounters were numbered #1 - #16 with #7 being divided into #7.1 and #7.2. According to the visual observers, there was only one focal pod tracked during encounter #7; however, in the thermal video recordings it turned out to be two different pods that were analysed separately and divided into #7.1 and #7.2. For the comparison of the thermal imaging based detection and visual detection, #7.1 and #7.2 are joined together to #7 resulting in 16 encounters.

Three encounters could only be analysed partially due to lack of corresponding thermal video recordings in the beginning (#1, #6) or in the end of the encounters (#10).

4.1 Behavioural response of fin and humpback whales to *RV Polarstern*

Consolidation of the 17 encounters yielded 752 events from the focal pods, as 203 events were considered to belong to animals outside the focal pods. The duration of the encounters ranged from only about 1 min (#6) to almost 30 min (#1), and focal pods were observed within a distance of up to 7000 m. The lowest number of events detected in one encounter was six (#3, #6), the maximum 296 (#1). The focal pods consisted of a minimum number of 2-8 animals (Tab. 6). Encounter #15 is the only encounter during which only events of the focal pod were detected.

During five encounters, the focal pods displayed a behavioural response to *Polarstern* and changed their orientation from swimming virtually parallel to *PS*'s path to moving perpendicularly away or moving into the opposite direction of the vessel (encounter #2, #4, #5, #7.1 and #7.2). The changes in direction ranged from a turn of 43° in encounter #5 to 98° in encounter #4.

During three of these encounters (#4, Fig. 21; #5, Fig. 23; #7.2, Fig. 25), the focal pod was detected ahead of *PS*'s path swimming in a similar direction. Due to *PS*'s higher speed, she was closing in on the pods which then turned away from the ship's path at an angle of 35°-71° between the ship's heading and the whales' position. The minimum distance between *PS* and

Tab. 6: Details of the 17 ship-whale encounters.
fin = fin whale; hb = humpback whale; PS = Polarstern

Encounter	**Number of events [total]**	**Number of events [focal pod]**	**Time between first and last detection of the focal pod [mm:ss]**	**Species**	**Min. number of animals in focal pod**	**Min. distance between *PS* and focal pod [m]**	**Max. distance between *PS* and focal pod [m]**
#1	342	296	29:50	fin	8	2698	7273
#2	85	58	09:07	fin + hb	6	504	3660
#3	9	6	10:07	n/a	2	3046	4509
#4	56	51	18:23	fin	5	1515	4152
#5	16	14	14:41	fin	2	1008	3343
#6	7	6	1:10	n/a	4	3863	4483
#7.1	58	24	26:41	hb	2	494	3615
#7.2		24	21:16	hb	2	670	3206
#8	10	9	3:38	hb	2	414	1430
#9	10	9	2:27	n/a	2	2570	3320
#10	37	32	16:56	hb	4	3603	5342
#11	17	14	4:56	n/a	4	3386	4468
#12	164	78	14:00	fin + hb	4	1851	3857
#13	29	21	15:32	fin	3	3389	5349
#14	51	49	15:58	fin	3	3605	6689
#15	14	14	4:52	hb	2	1198	3201
#16	50	47	20:34	hb	6	3387	5346
total	**955**	**752**					

the focal pods ranged from ~670 m to ~1520 m. The models of encounter #4 (Fig. 22) and #7.2 (Fig. 26) show the paths of the pods based on events detected during the first part of the encounters. According to the models, the pods would have moved on in the same direction, virtually parallel to *Polarstern*'s path and do not reflect that the whales changed their orientation and turned away from the *PS*. During encounter #5, only a few events were recorded after the change of direction that can be compared to the modelled movement of the pod (Fig. 24). Even though some of the modelled paths reach the last detections of the whales, the model does not reflect the behavioural response of the pod as it changed its swimming direction.

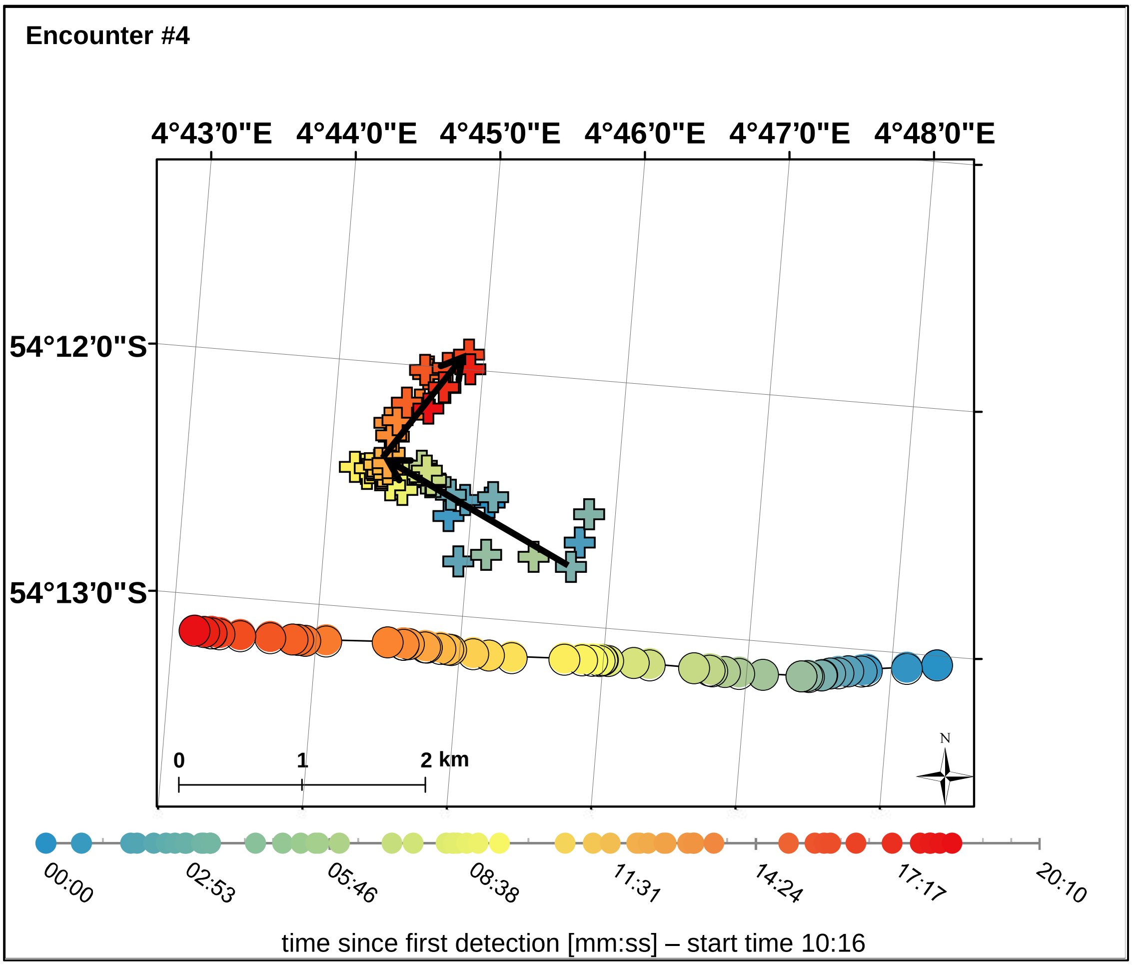


Fig. 21: Geo-referenced map of encounter #4[1], fin whales, 18:23.

Coloured circles mark positions of *Polarstern* along her route, coloured crosses mark the track of a pod of fin whales (each beginning with blue). Colour represents time, i. e. circles and crosses with the same colour mark *Polarstern*'s position and a whale's position at the same time[2].

A pod of five[3] fin whales displaying a behavioural response to *Polarstern*. The ship approached the pod which was traveling in the same direction. At an angle of 71°, when the distance between the ship and the pod was about 1500 m, the pod changed its orientation by 98° and moved away from the ship's path (indicated by black arrows).

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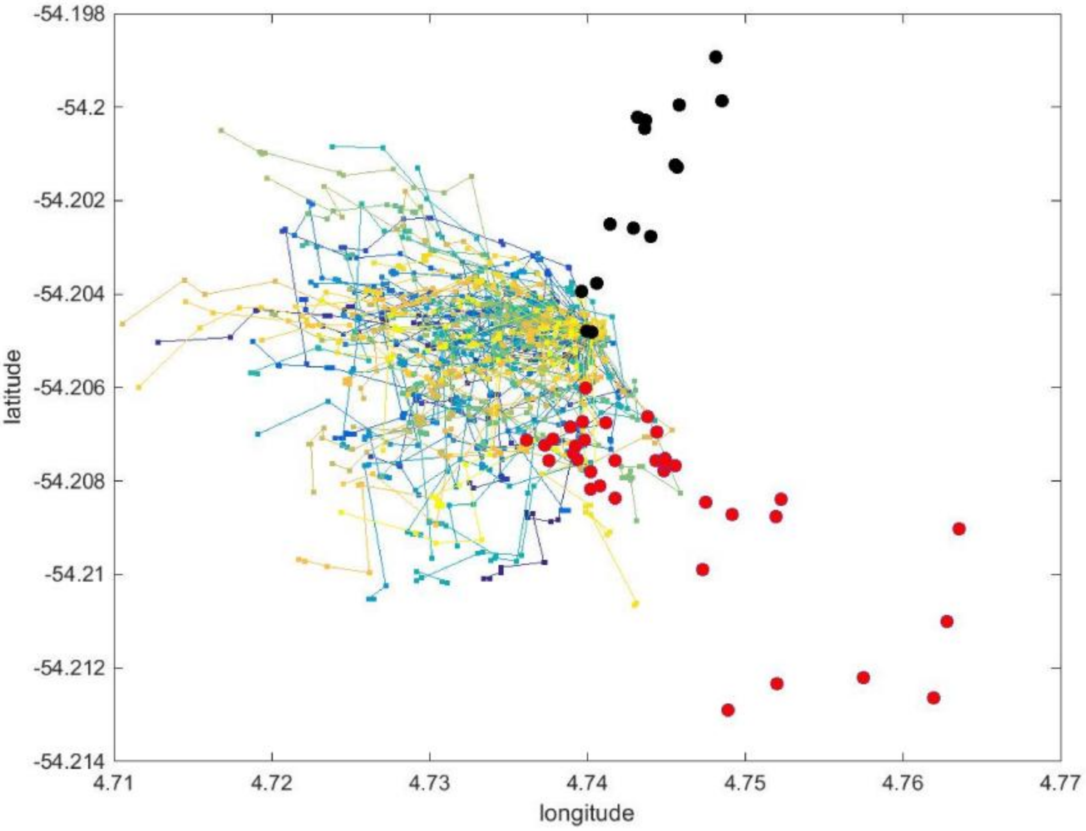
[1] For better recognition, the scale of the maps was adapted to the distance that was covered during each encounter.

[2] This description applies to the figures of all encounters.

[3] Number of animals in a pod is a minimum number based on the time between blows and swimming speeds of the animals



Model #4

Fig. 22: Geo-referenced map of the model of encounter #4.

Red marks indicate events detected in the thermal stream that were used as basis for the modelling, black marks indicate events detected in the thermal stream in the end of the encounter that were not included in the modelling process; blue, green and yellow marks indicate modelled events, i.e. possible paths of the whales, of 100 modelling runs[4].

According to the modelled events, the whales would have kept swimming with a preferred direction. Instead, they changed their travel direction and turned away from *Polarstern'*s path.

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[4] This description applies to the figures of all models.

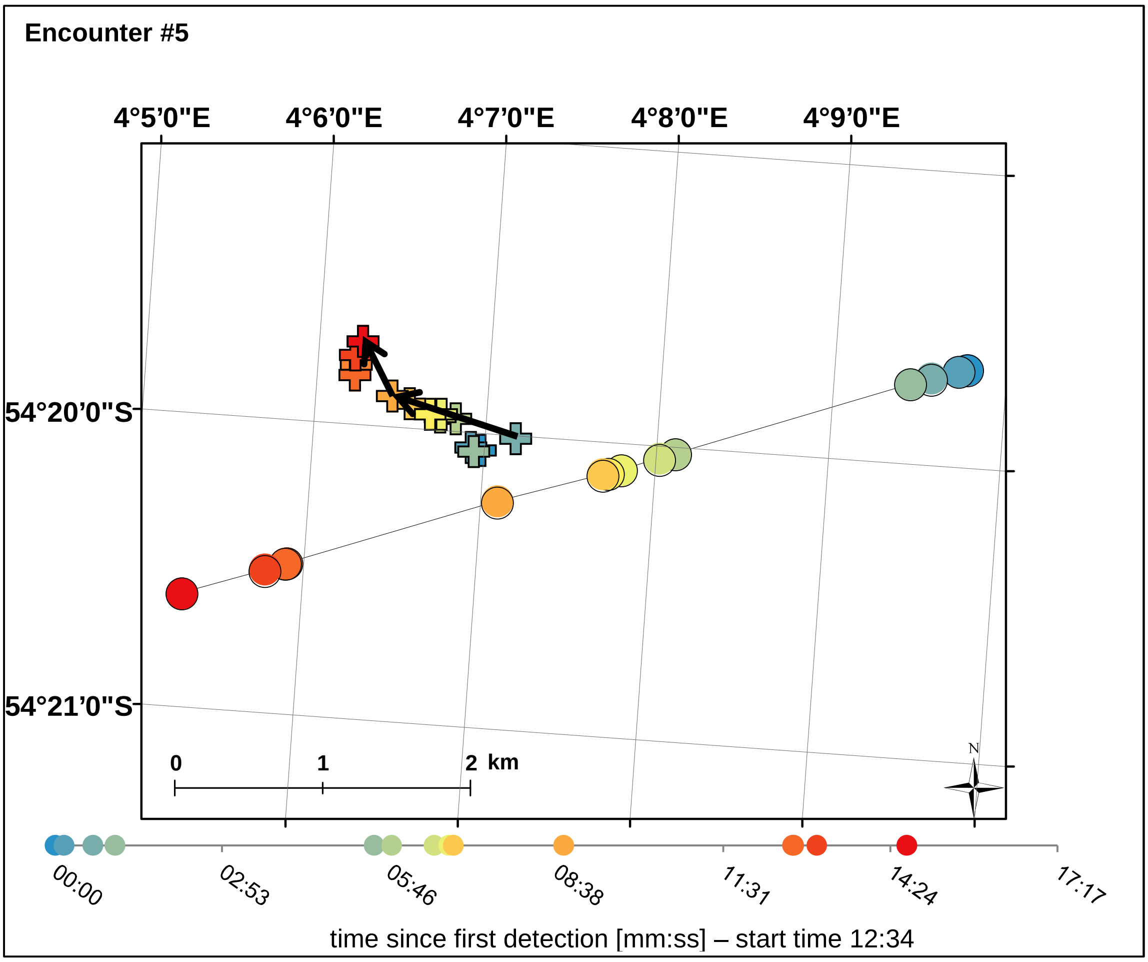


Fig. 23: Geo-referenced map of encounter #5, fin whales, 14:41.

A pair of fin whales showing a behavioural response towards *Polarstern*. *PS* approached the two fin whales which were traveling in a similar direction but away from the ship's path. When *Polarstern* came closer, the pod made a turn and moved virtually perpendicular away from her path (indicated by black arrows). The shift in orientation by 43° occurred at an angle of 62° between the pod and *PS* when the distance was about 1000 m.

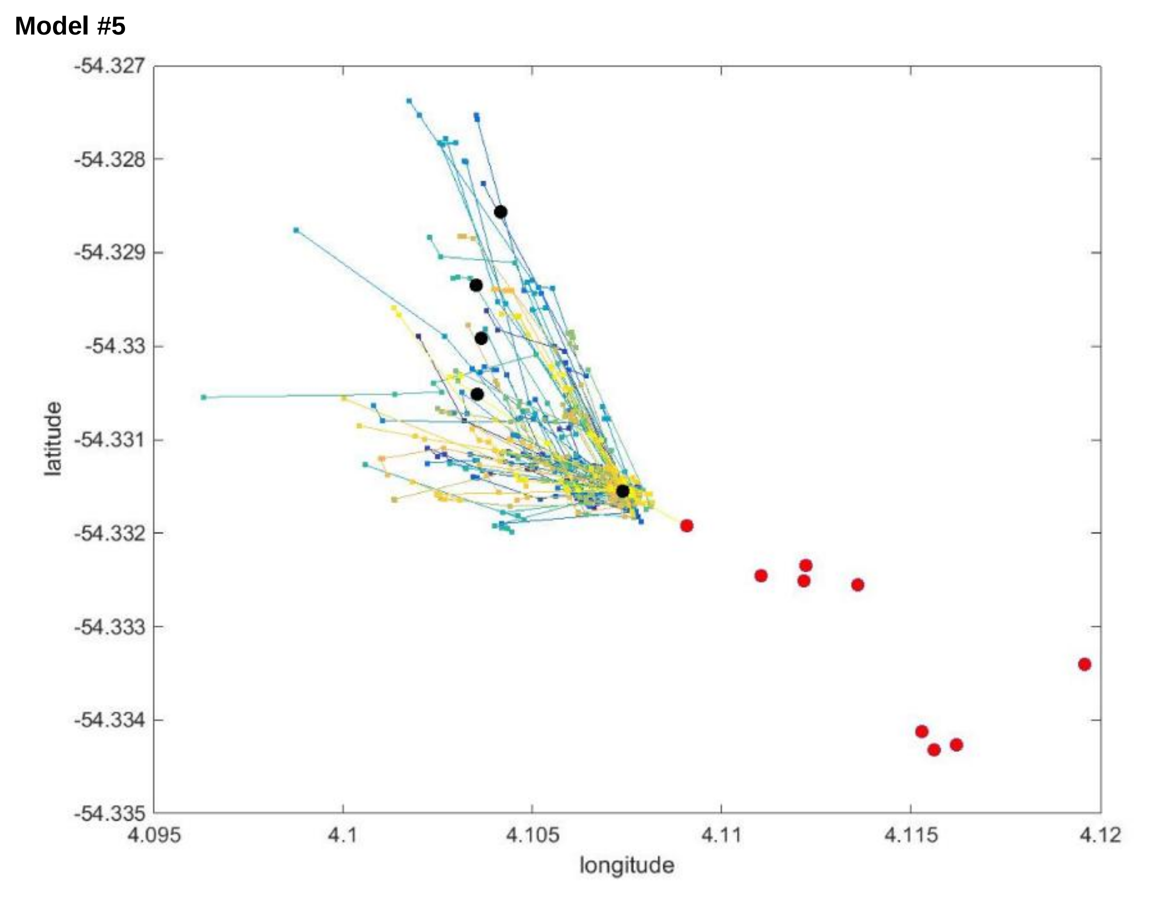


Fig. 24: Geo-referenced map of the model of encounter #5.

The modelled events and the detected events do not match as the modelled events have the same directionality as the events that they are based on. However, the whales actually turned away from the ship’s path in the end of the encounter.

Encounter #7.2

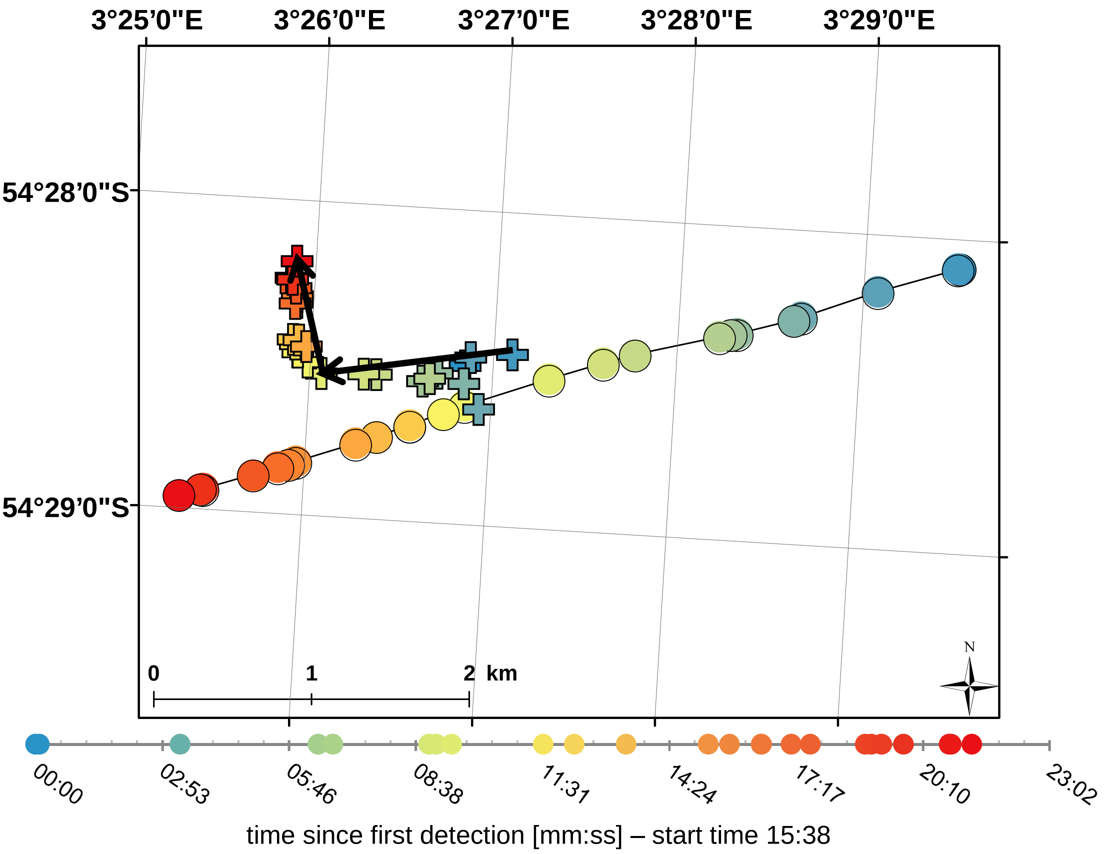


Fig. 25: Geo-referenced map of encounter #7.2, humpback whales, 21:16.
Polarstern approached a pod of two humpback whales moving into the same direction as the ship. When *Polarstern* came closer and the angle between the ship and the pod was 35° at a distance of about 1040 m, the whales turned away by 87° and moved almost perpendicularly to the ship's path (indicated by black arrows).

Model #7.2

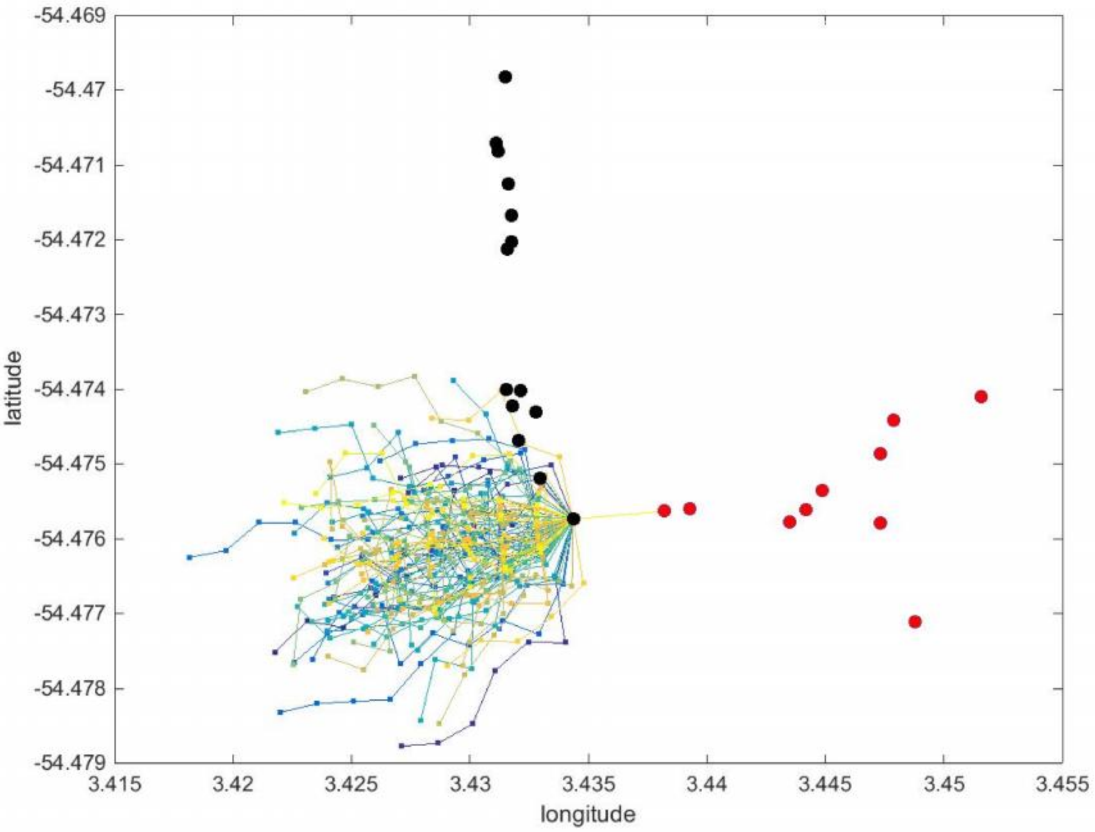


Fig. 26: Geo-referenced map of the model of encounter #7.2.

The modelled events and the actually detected events do not match. The modelled events have the same direction as the events they are based on and do not reflect that the whales turned away.

During encounter #2 (Fig. 27), the focal pod and *PS* were moving towards each other. When the distance was about 880 m, the whales made a turn away from the ship's path at an angle of ca. 22°. When the along-track-distance between *PS* and the pod was about 0 m, the whales shifted their orientation again to the opposite direction of *PS*'s heading. The modelled events of encounter #2 (Fig. 28) covered an area much larger than the area in which the whales were tracked. All detected events are covered by the modelled events. The model allows for both swimming directions, towards and away from *Polarstern*. As after the animals made a turn to the right, they shortened the distance covered between two surfacings, the model is not capable of grasping that change and allows for a much wider distribution of possible positions.

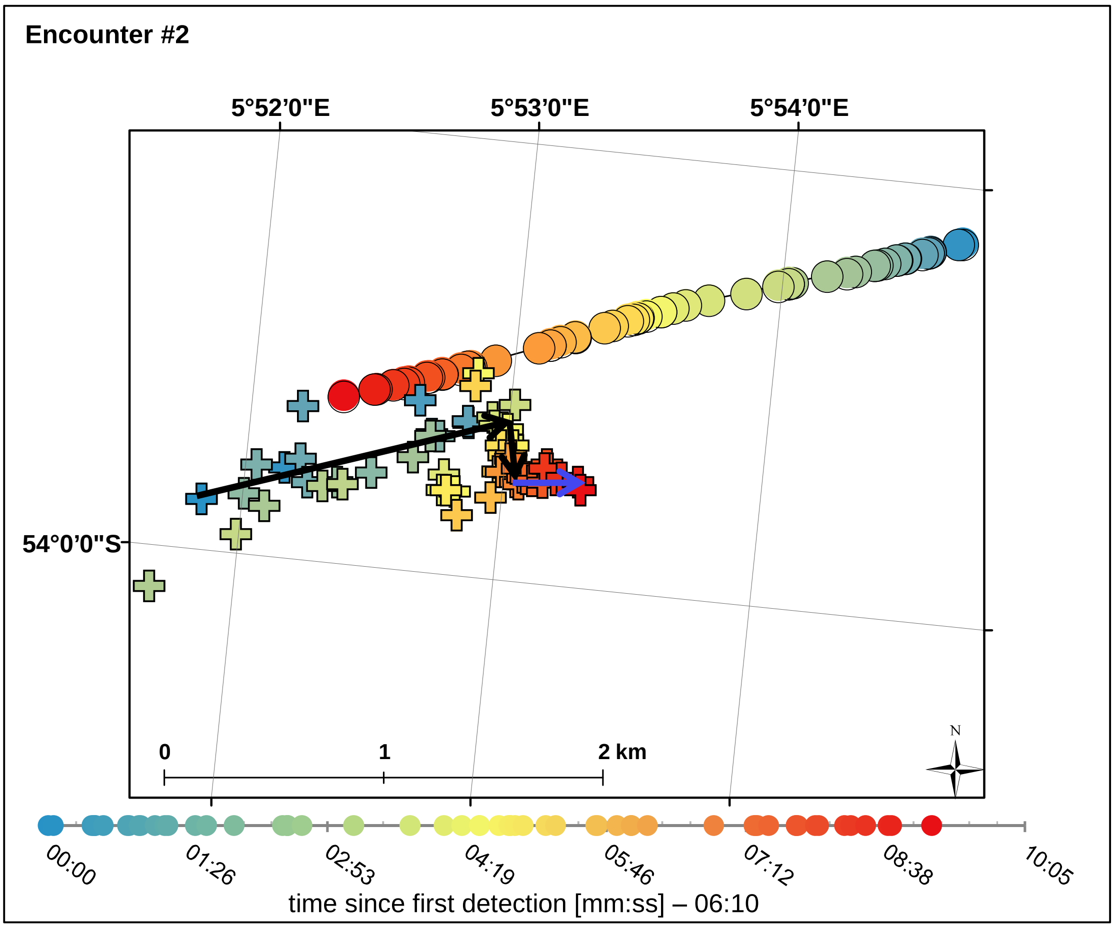


Fig. 27: Geo-referenced map of encounter #2, fin and humpback whales, 09:07.
A pod of six whales was ahead of *Polarstern*'s path as they were moving towards each other. When the distance between the pod and *PS* was only about 880 m at an angle of ca. 22°, the pod showed a behavioural response by making a turn of almost 90° away from *PS*'s path (indicated by black arrows). As *PS* came closer and reached the same level as the pod, the whales shifted their orientation again (74°, indicated by blue arrow) and moved to the opposite direction of the ship.

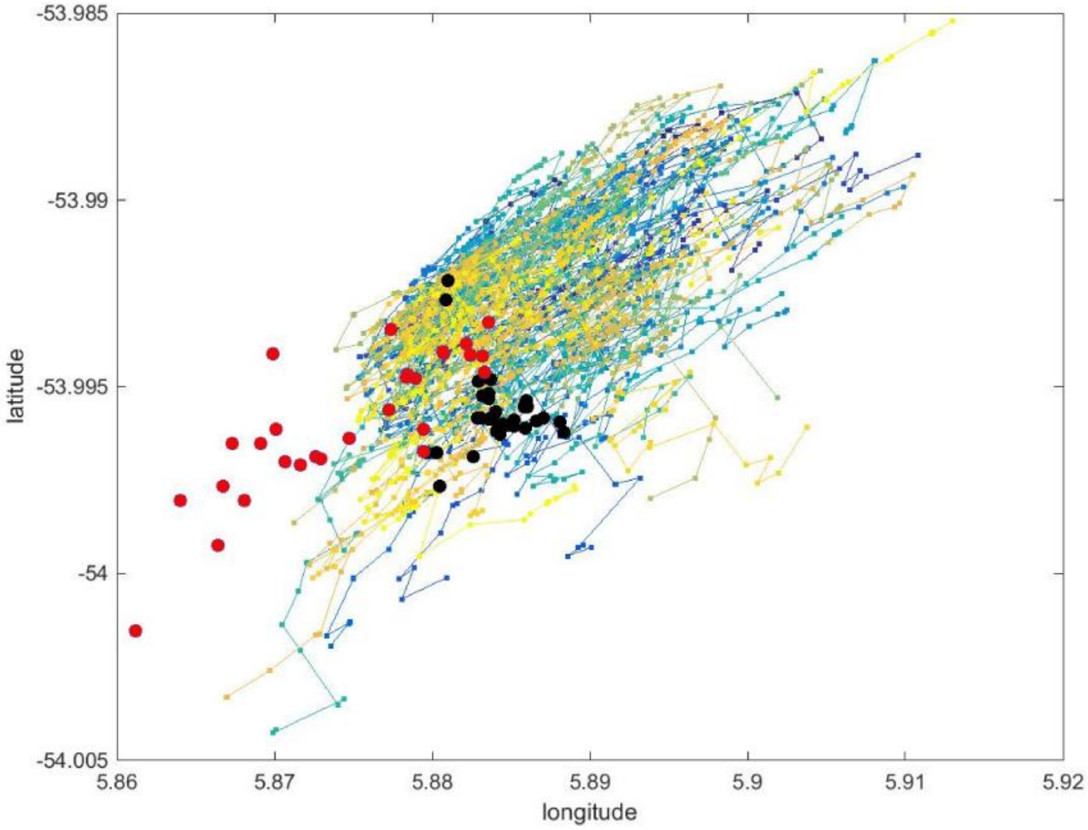

Model #2

Fig. 28: Geo-referenced map of the model of encounter #2.
The modelled events do not show a clear direction and cover up all detected events. The covered area is also much larger than the distance actually travelled by the whales.

During encounter #7.1 (Fig. 29) the pod did not travel parallel to *PS*'s path but was virtually stationary ahead of her path for approx. 13 min before starting to move perpendicularly to *PS* when the distance was only about 920 m. When *PS* and the pod where ca. at the same level (along-track-distance of 0 m), they turned to the opposite direction of her path. The fact that there was no other pod recorded during this time, and that the direction change is already indicated in the events before the last detection suggest that all events belonged to the same pod that changed its travel direction. Similar to encounter #5, only a few events were recorded after the whales had shifted their orientation that can be compared to the model of the pod (Fig. 30). Assuming that whales kept swimming in the direction of the last events, however, the model and the detected events show different movements of the pod.

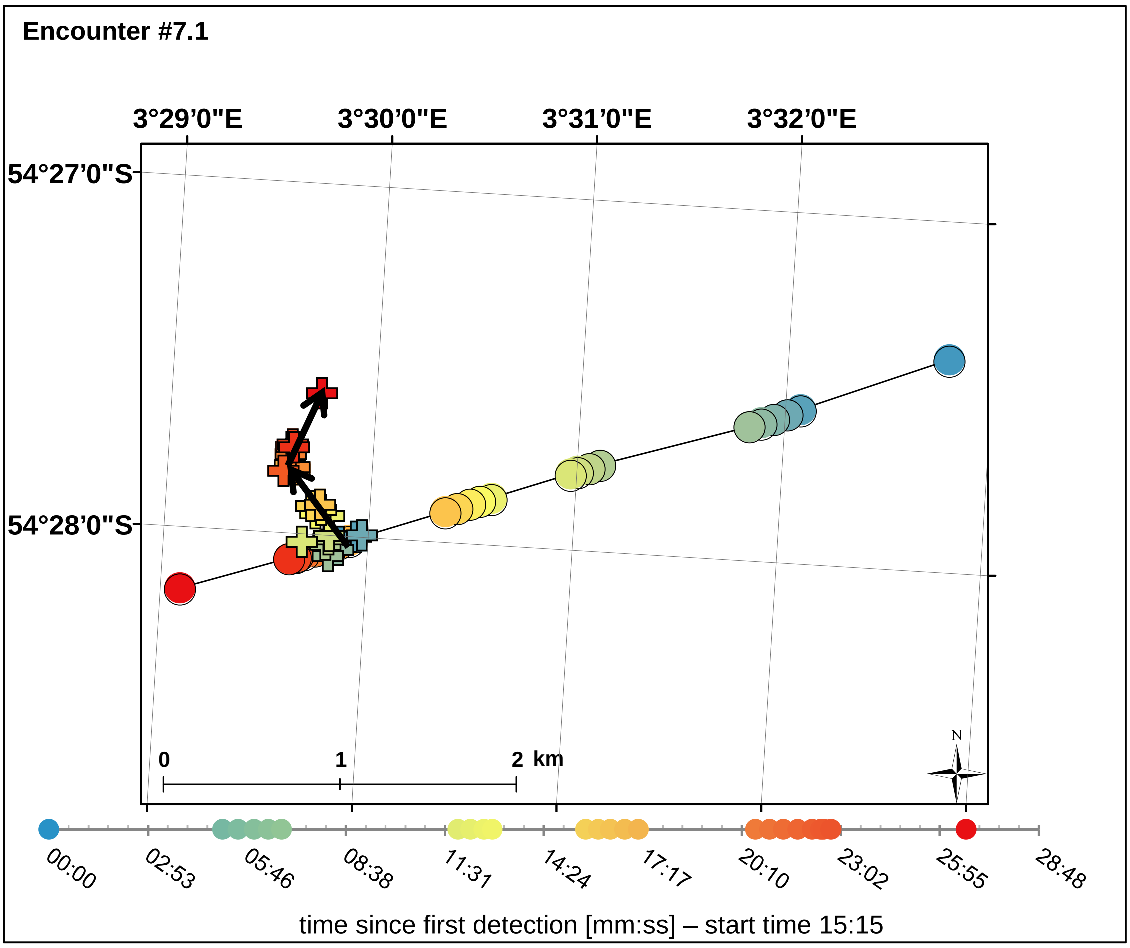


Fig. 29: Geo-referenced map of encounter #7.1, humpback whales, 26:41.
A pod of two stationary humpback whales was approached by *Polarstern*. As the ship came closer, the whales moved virtually perpendicularly to its path until the distance of *PS* was only about 550 m at an angle of 67°. Then, the pod shifted its orientation by 55° and turned towards the opposite direction than the ship (indicated by black arrows).

Model #7.1

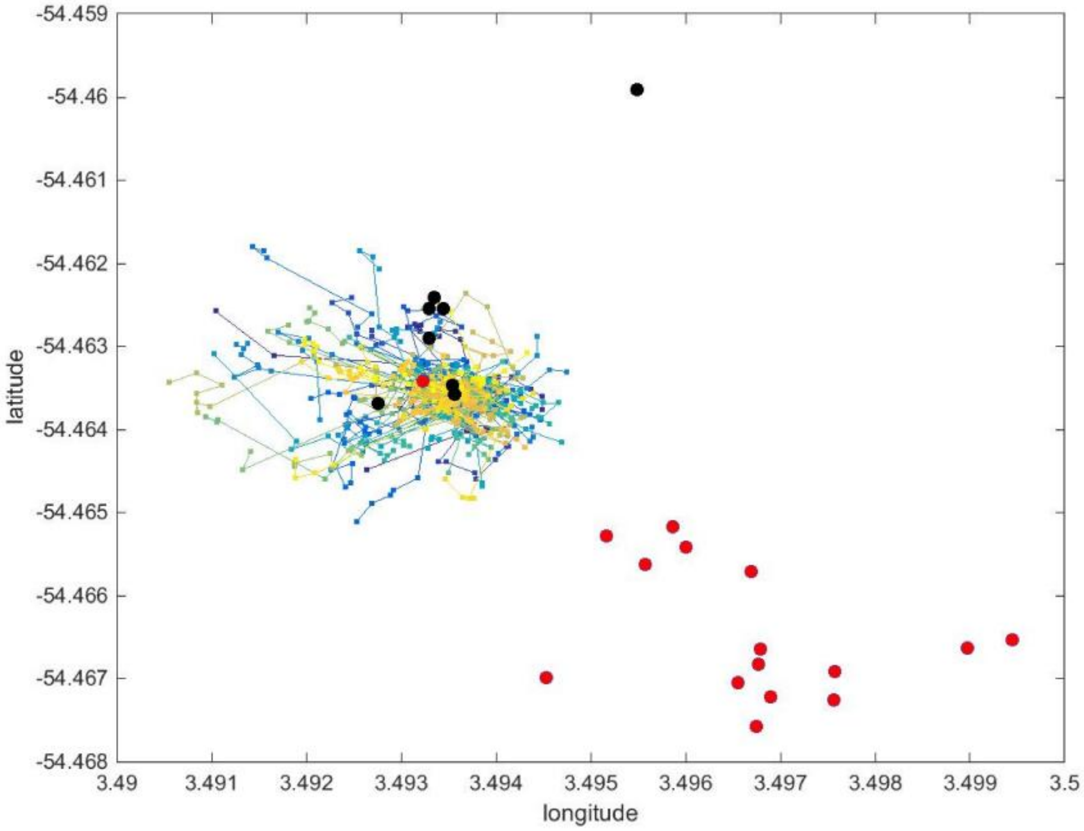


Fig. 30: Geo-referenced map of the model of encounter #7.1.

Even though most of the events after the offset are covered by the modelled events, it seems like the whales changed their direction away from the ship's path in the end of the encounter. This change is not consistent with the modelled events.

During encounter #1 (Fig. 31), a pod of at least eight fin whales was tracked which seemed to move away from *PS* before turning back in the end of the observation. Similar to the model of encounter #2, the model of #1 (Fig. 32) covers a large area. Even though the whales appeared to turn right during the encounter, the modelled events do not reflect this observation. However, the vast majority of the detected events are covered up by the modelling.

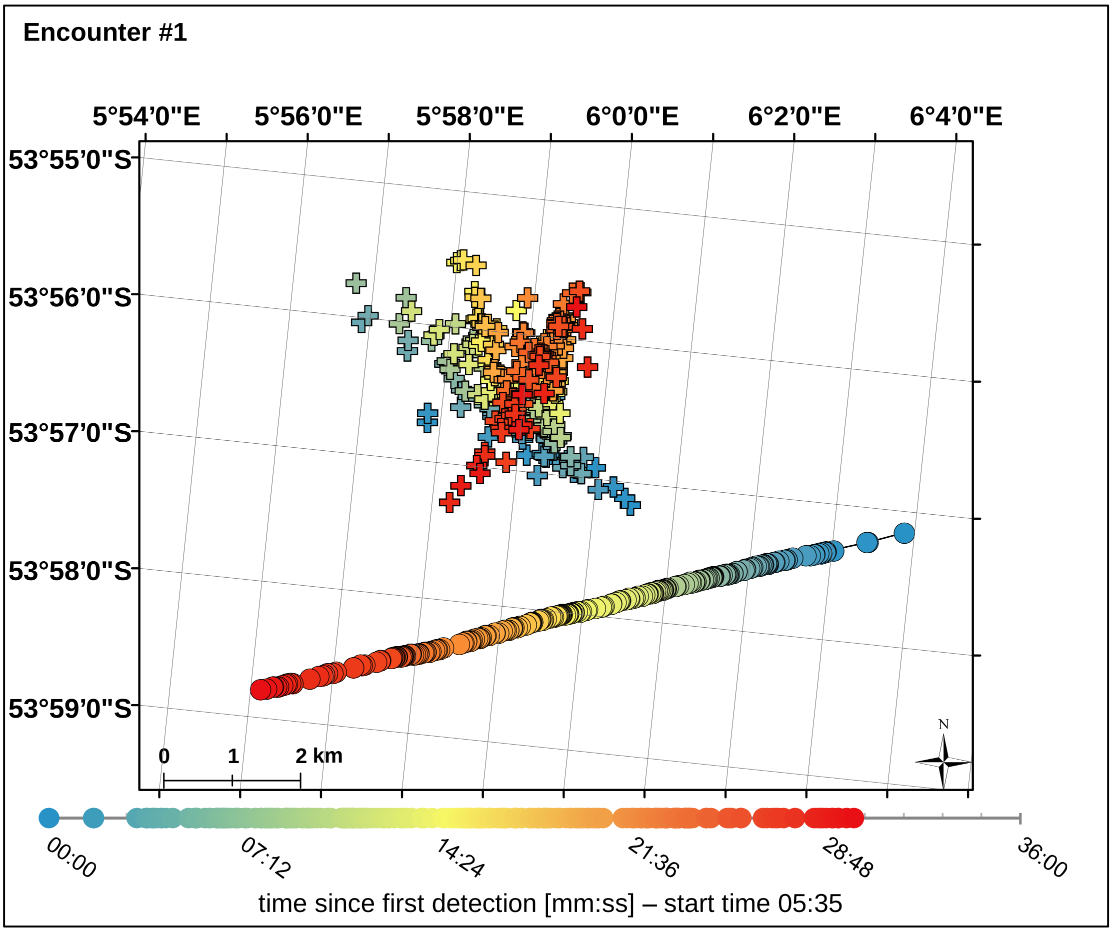
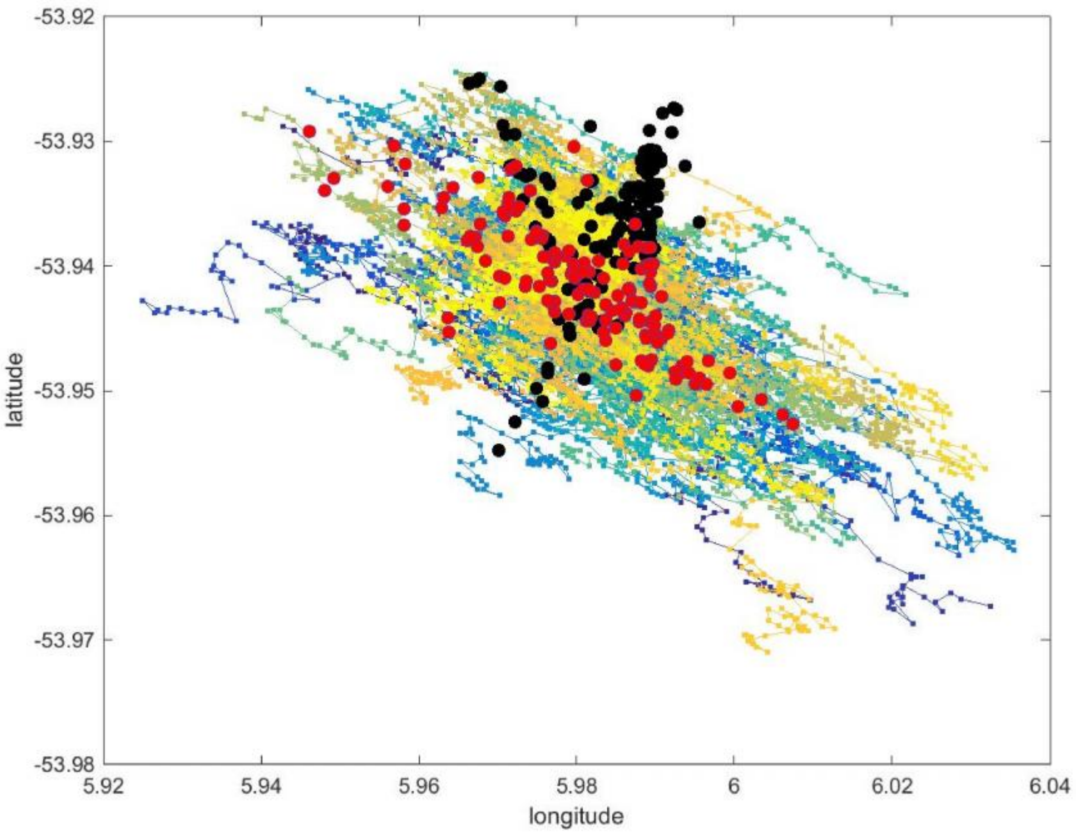


Fig. 31: Geo-referenced map of encounter #1, fin whales, 29:50.
A pod of eight dispersed fin whales seemed to first turn away from *PS*'s path before turning again and heading into the same direction in the end of the encounter.



Model #1

Fig. 32: Geo-referenced map of the model of encounter #1.

Almost all of the black events that were not included in the modelling process are covered by the modelled events. However, the modelled events show a great variability in the movement of the whales.

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During encounter #13 (Fig. 33), a pod of three fin whales was detected at ~30° in a distance of about 4000 m traveling obliquely in a similar direction as *Polarstern*. However, at an angle of ~43° the pod seemed to make a turn and swim perpendicularly away from *PS*'s path. The model of #13 (Fig. 34) does not match this movements of the pod. According to it, the whales would have kept swimming in the same direction or turned back. However, this encounter was thought to consist of two different pods by the visual observers suggesting that one pod was traveling obliquely away from *Polarstern*'s path and one pod was in a greater distance.

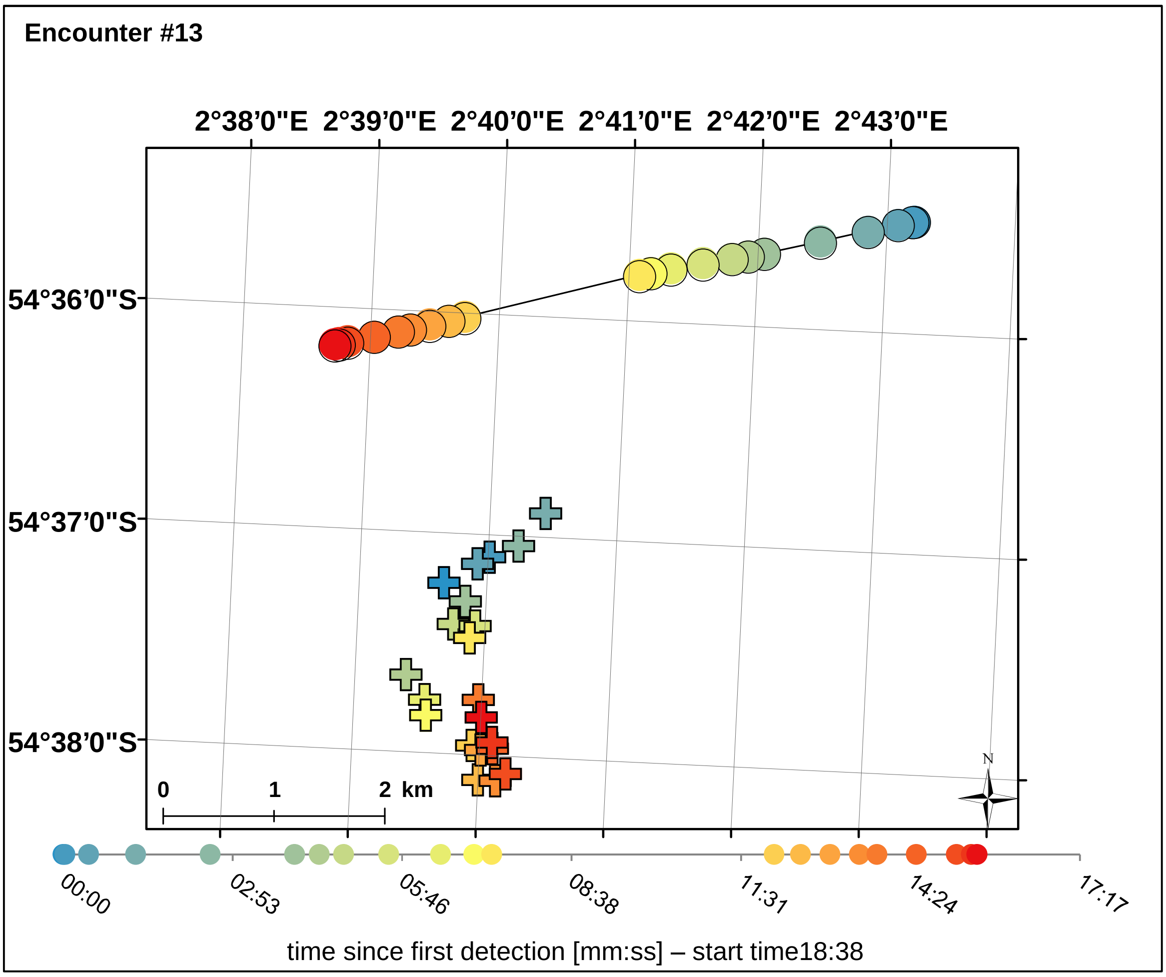

Fig. 33: Geo-referenced map of encounter #13, fin whales, 15:32.
A pod of three fin whales was detected at ~30° in a distance of about 4000 m traveling obliquely in a similar direction as *Polarstern*. When the ship approached and the angle increased to 44°, the pod made a turn and swam perpendicularly away from the ship's path. However, according to the visual observers, the events detected in the end of the encounter belong to a different pod.

Model #13

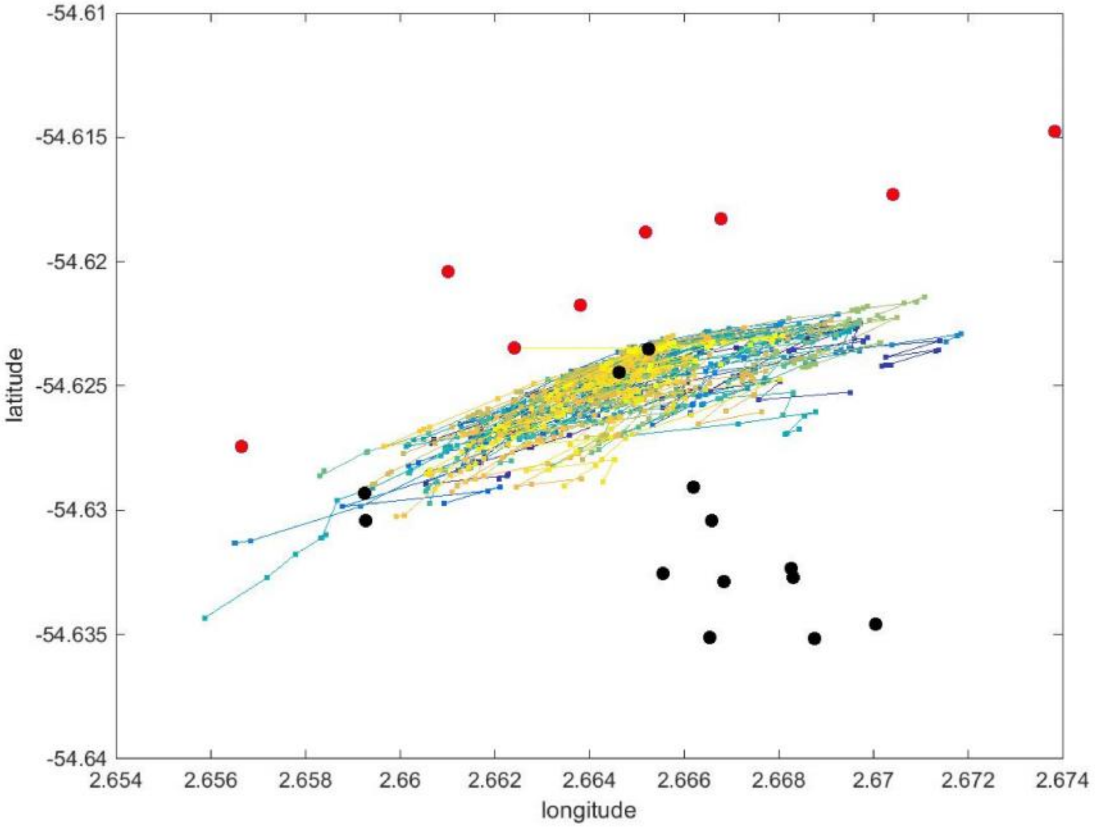

Fig. 34: Geo-referenced map of the model of encounter #13.

The model is not in consistency with the actual events of the encounter. The pod made a turn away from *Polarstern*'s path which is not reflected by the modelled events. According to the model, the whales would have maintained their direction or would have turned back. However, the recordings of the visual observers suggest that the events detected in the end of the encounter belong to a different pod.

Two other focal pods (#8, Fig. 35; #12, Fig. 37) were traveling in a constant direction without changing their orientation during the observation. During #8, the focal pod was detected in ~1430 m at 30° and was moving towards *Polarstern*. Over the course of ~4 min, the distance between the pod and the ship decreased to ~410 m and the angle increased to ~96° before the observation stopped. The focal pod of 12# was tracked in a range from ~34°-118°. During this time, the distance to the pod declined from about 3000 m to a minimum of ca. 1850 m as *Polarstern* passed by it. During the 14 min of observation, the pod travelled virtually perpendicu-

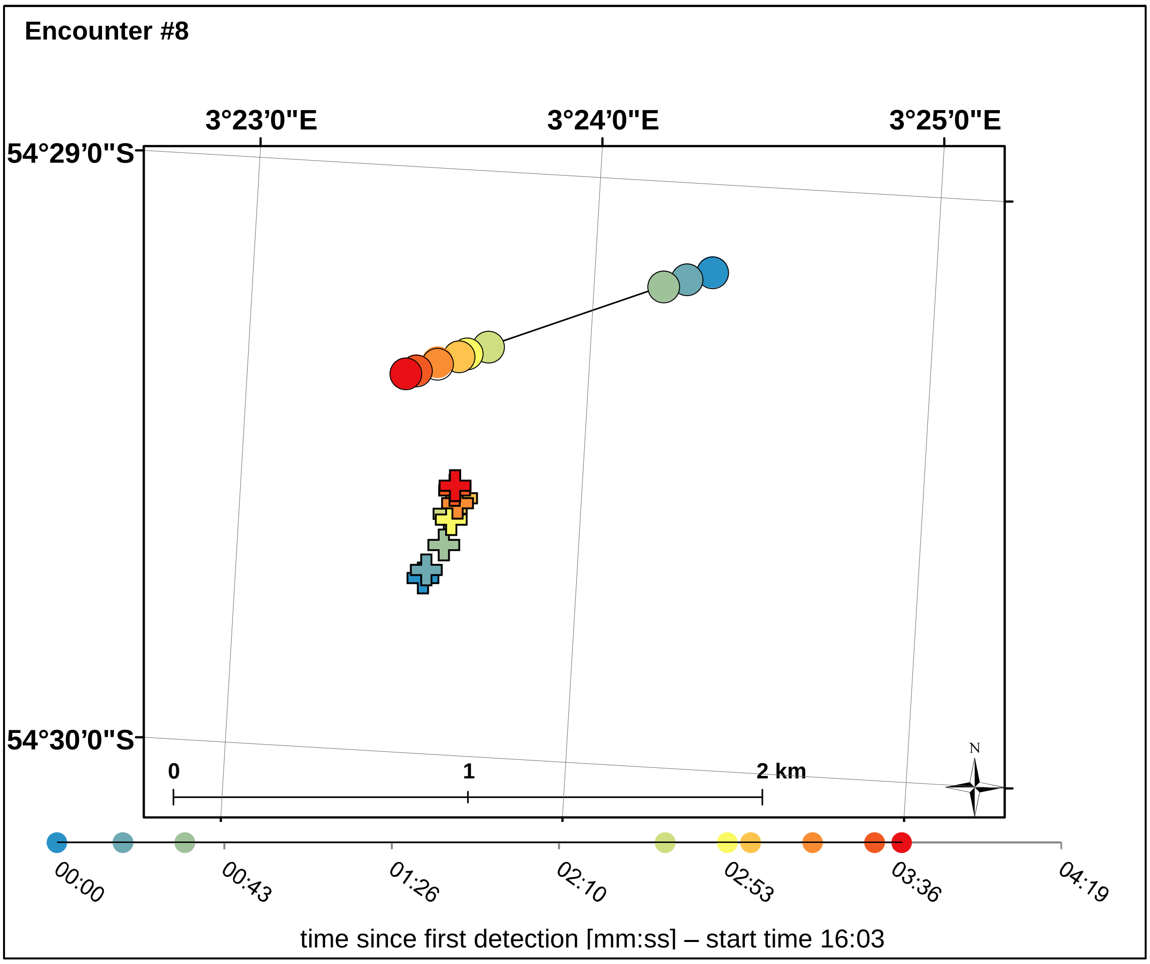

Fig. 35: Geo-referenced map of encounter #8, humpback whales, 3:38.
A pod of two humpback whales moved obliquely towards *Polarstern*'s path. The animals seemed to move in a virtually straight line with a slight turn to left in the end of the encounter.

larly away from the vessel's path and was last seen at distances between 3600 m and 3860 m. Events recorded in the last five minutes of this encounter were excluded from the analysis because they could not be assigned to a certain pod. The models of encounter #8 (Fig. 36) and 12 (Fig. 38) match the events detected in the thermal images. The modelled events of #8 reflect the travel direction that was recorded in the pod. However, the two events detected last fit the model less well as the whales seemed to turn left. During encounter 12, the direction of travel is also the same for the detected and the modelled events even though not every detected event is covered by the model.

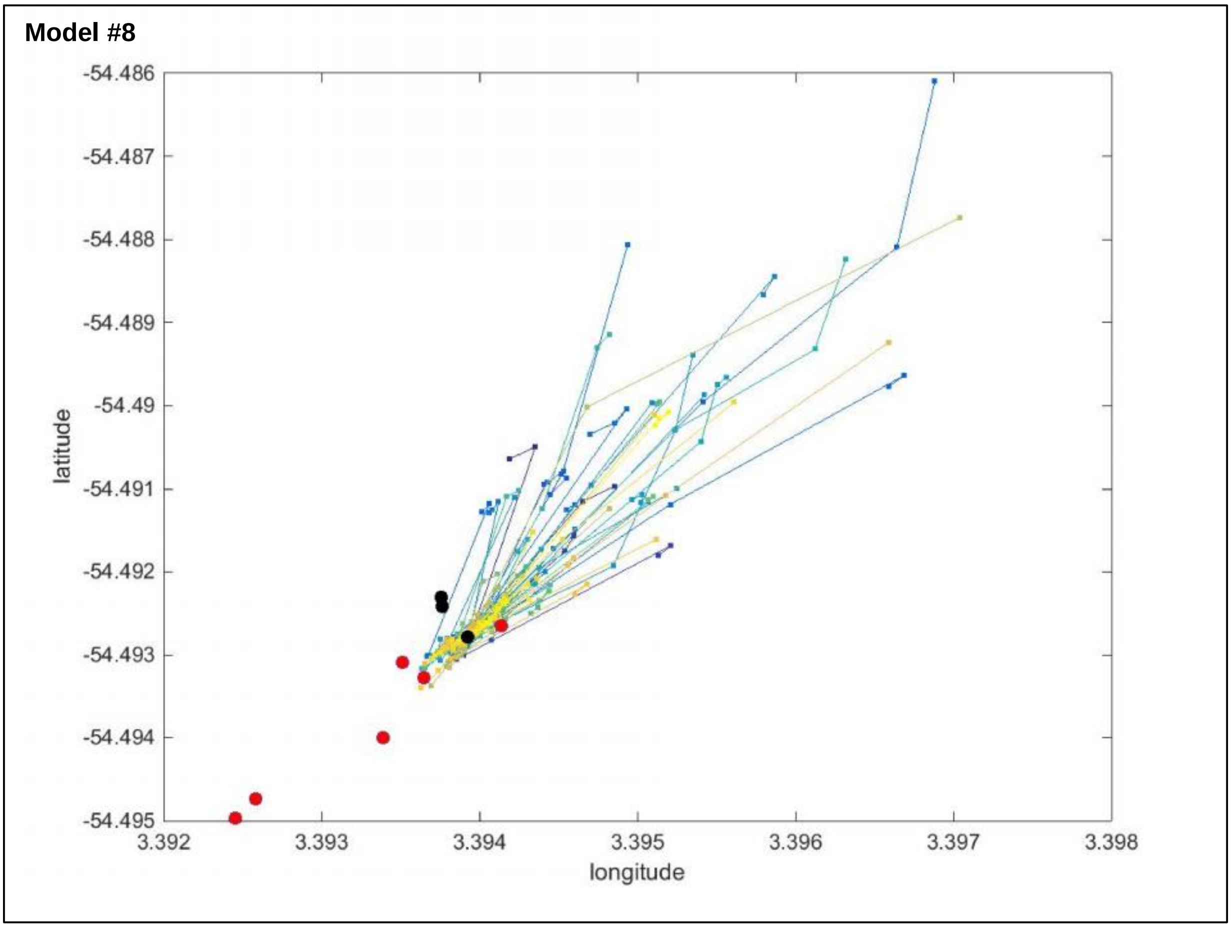

Fig. 36: Geo-referenced map of the model of encounter #8.
The modelling matches the movement of the whales which were traveling in a virtually constant direction. It seems like the animals made a slight turn to the left in the end of the encounter.

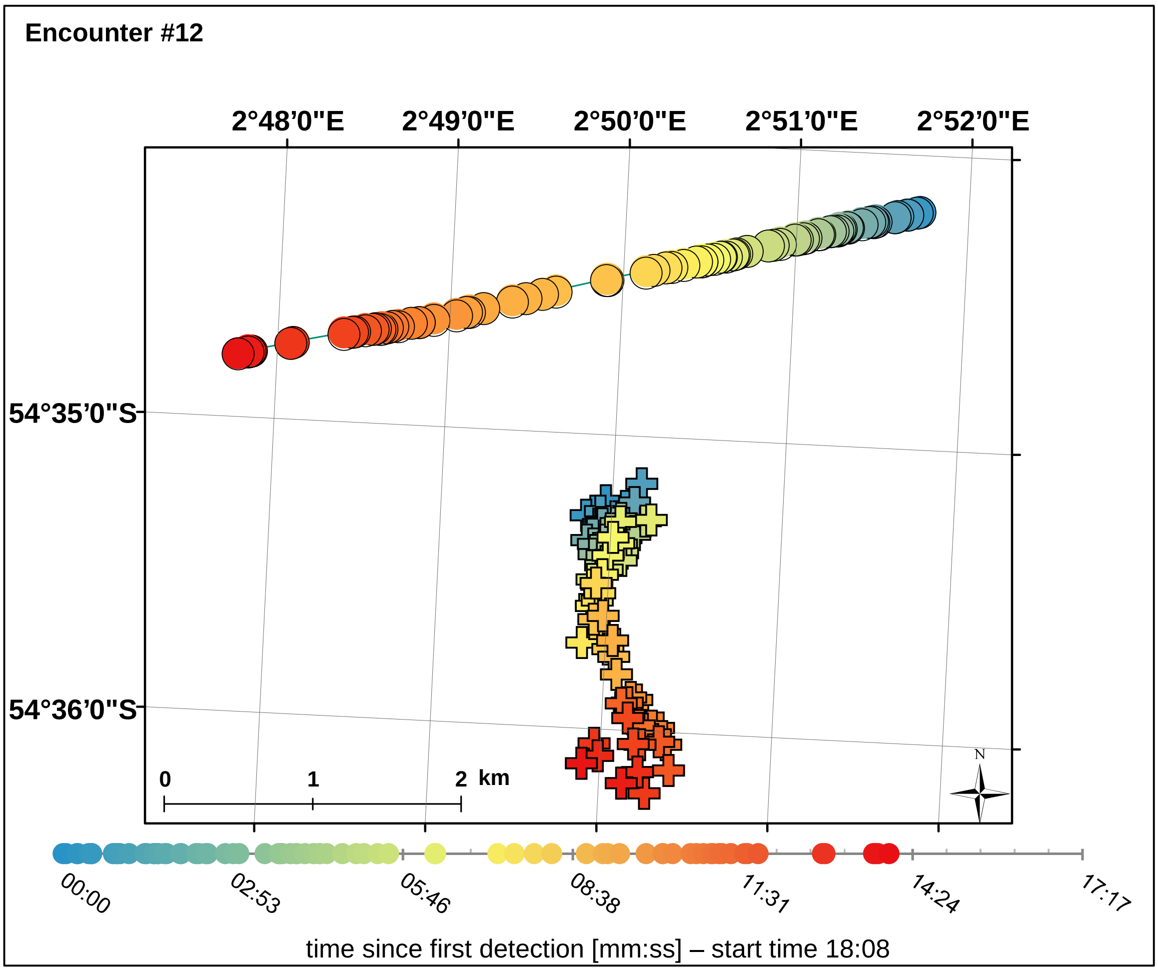

Fig. 37: Geo-referenced map of encounter #12, fin and humpback whales, 14:00.

A pod of four fin and humpback whales was detected in about 3000 m distance and was swimming away from the *Polarstern*’s path perpendicularly. While *PS* came closer and passed by the pod, the whales kept swimming in the same direction.

The last five minutes of recordings were excluded from the analysis since the events detected during this time could not be assigned to a particular pod.

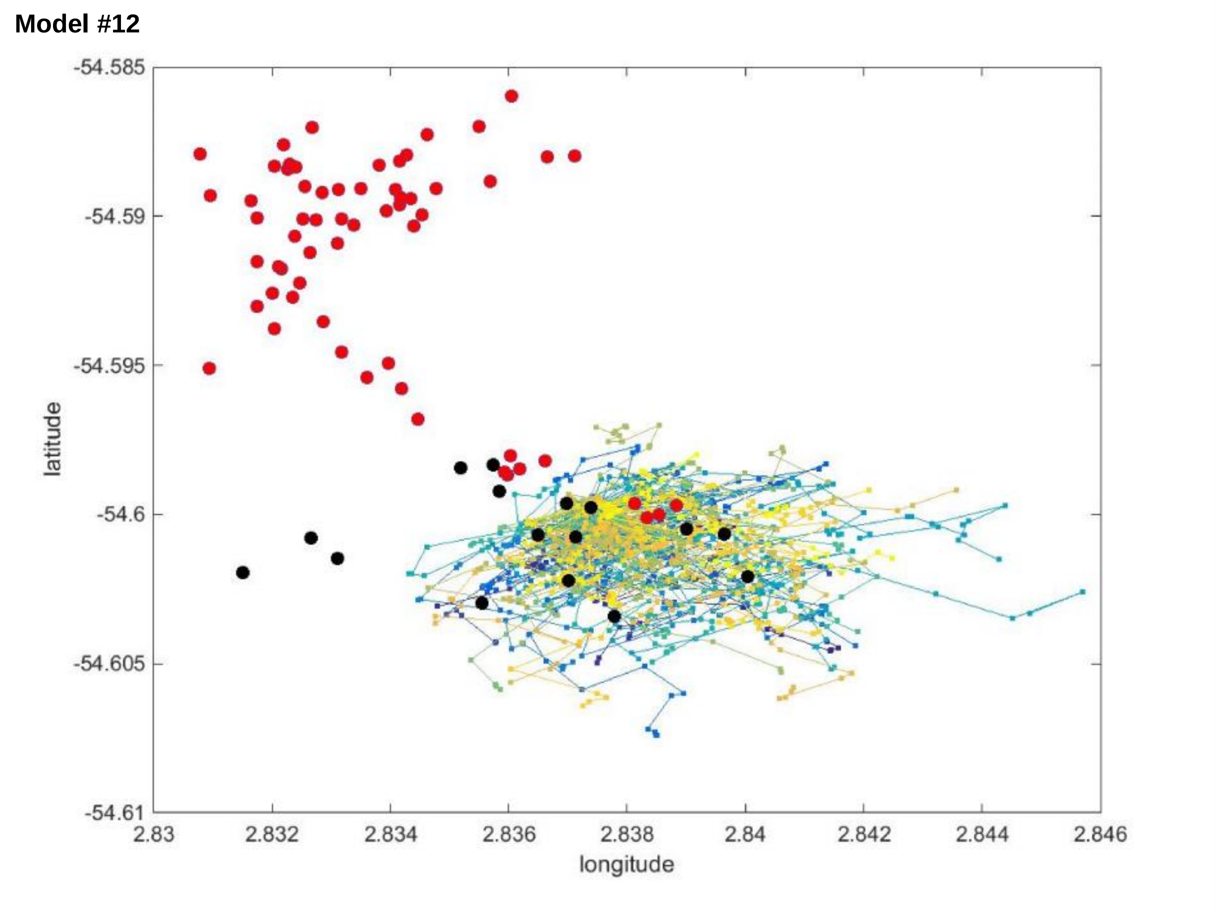

Fig. 38: Geo-referenced map of the model of encounter #12.

Most of the events detected in the end of the encounter are covered by the model. A part of the pod seemed to turn to the left which is not consistent with the modelled events.

During the encounters #10 (Fig. 39), #11 (Fig. 41), #14 (Fig. 43), #15 (Fig. 45) and #16 (Fig. 47), the focal pods were rather stationary. They did not appear to travel directionally but remained in the same area. These pods were sighted at minimum distances ranging from ~3390 to ~3600 m, and the observations started at angles >45°, except in #15. During encounter #15, *Polarstern* approached the pod to a minimum distance of ~1200 m at an angle of about ~53° before the observation stopped. There is a general consistency between all of these pods and their respective models, even though the pod of #10 seemed more stationary than in the model (Fig. 40). The models of #11 (Fig. 42), #14 (Fig. 44), #15 (Fig. 46), #16 (Fig. 48) reflect the rather stationary behaviour of each of the focal pods. One event that appears offside of the modelling of encounter #14 also seems offside of the detected events.

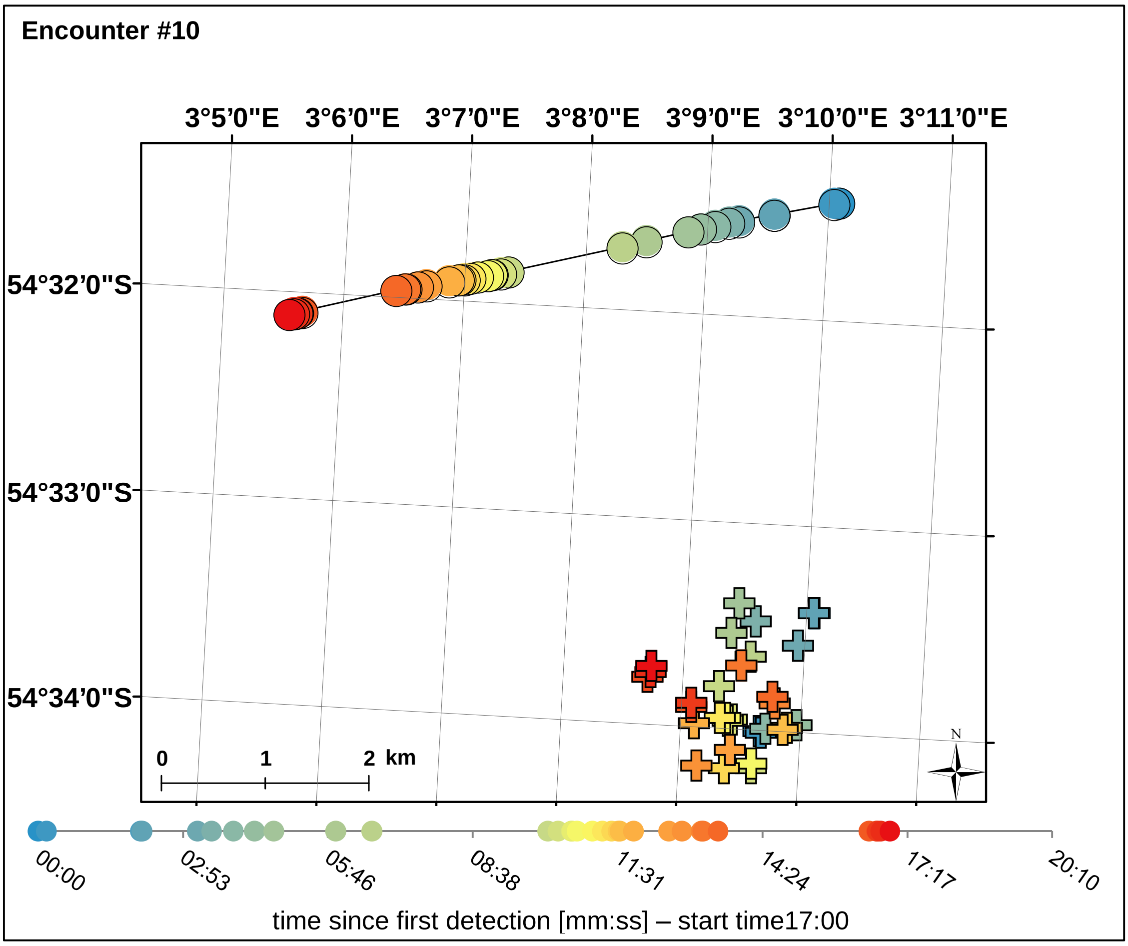

Fig. 39: Geo-referenced map of encounter #10, humpback whales, 16:56.
Polarstern passed by a pod of four humpback whales. Even though the whales moved slowly into the same direction as the ship, they appeared rather stationary than traveling to a specific direction. The distance between *PS* and the pod ranged from 3600 to 5340 m.

Model #10

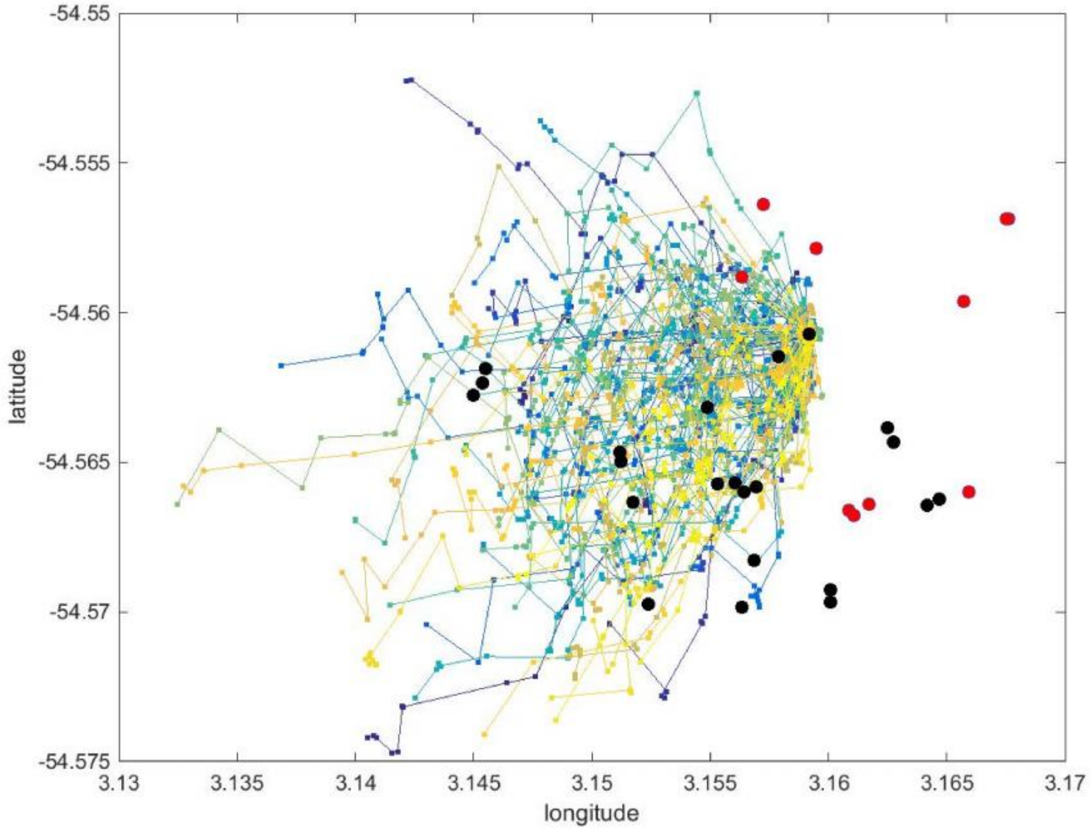

Fig. 40: Geo-referenced map of the model of encounter #10.

The modeled events by trend match the actual events, even though the pod seemed to be more stationary than the modeled events suggest.

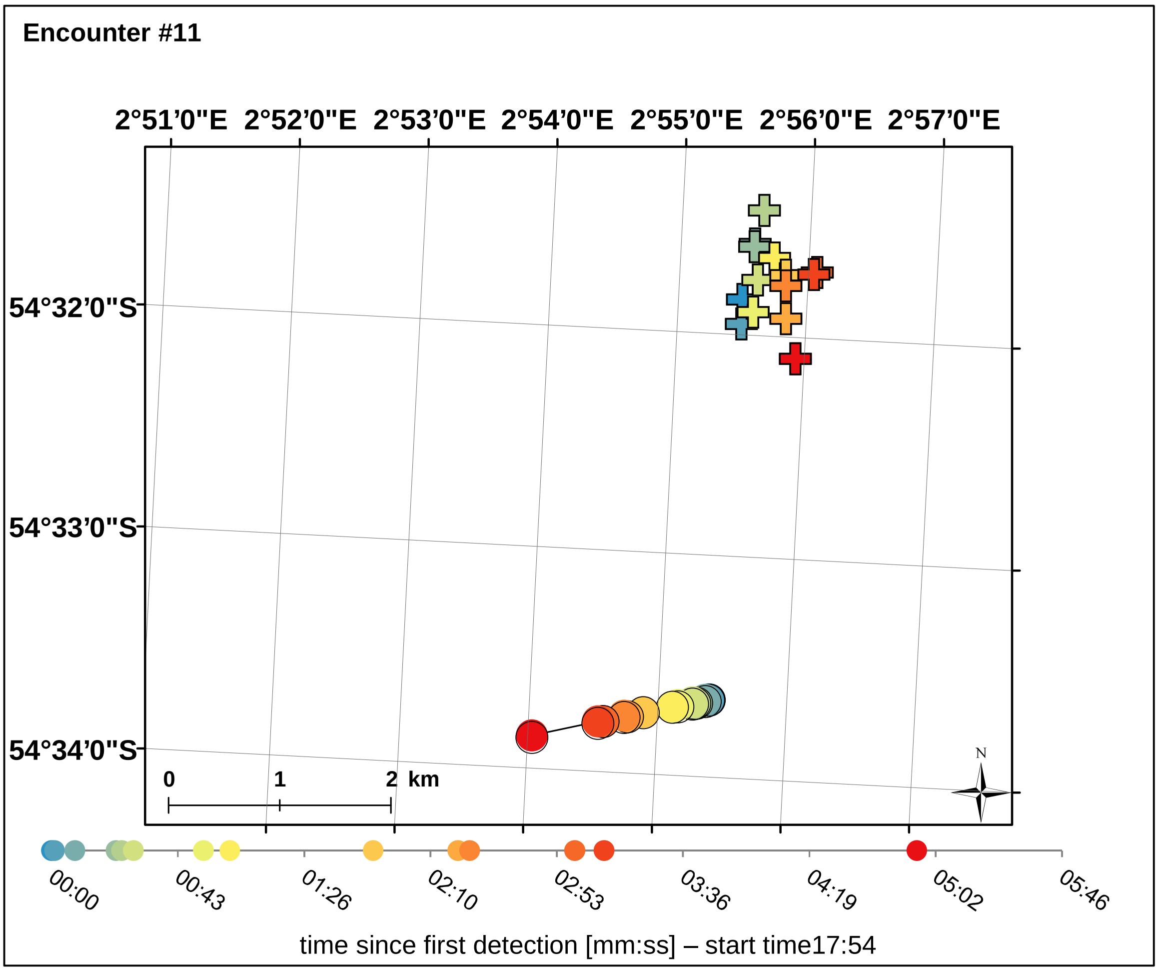

Fig. 41: Geo-referenced map of encounter #11, unidentified species, 4:56.
A pod of four whales was detected in a distance of ~3600 m at an angle of ~106°. While *Polarstern* moved on and the distance increased, the pod moved into the opposite direction but remained in the same area.

Model #11

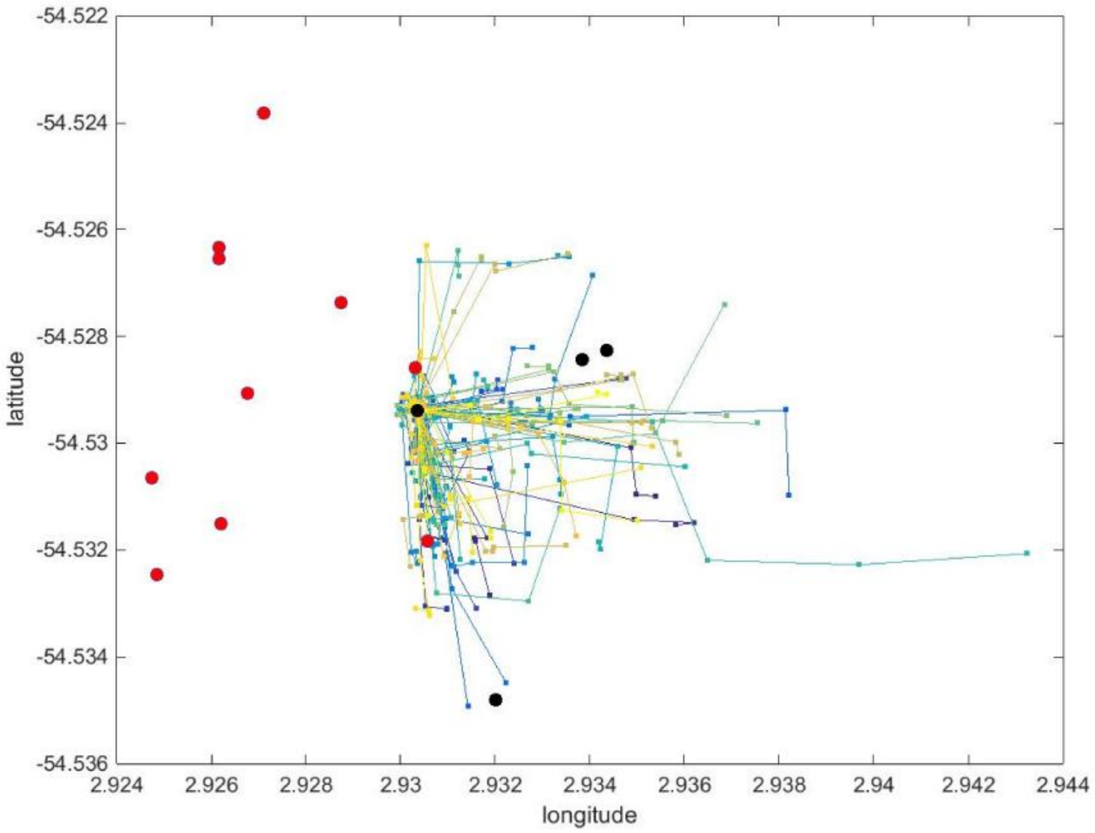

Fig. 42: Geo-referenced map of the model of encounter #11.
The modelled events are generally consistent with the events detected in the thermal images. The pod’s movement to the right reflected by the modelled events.

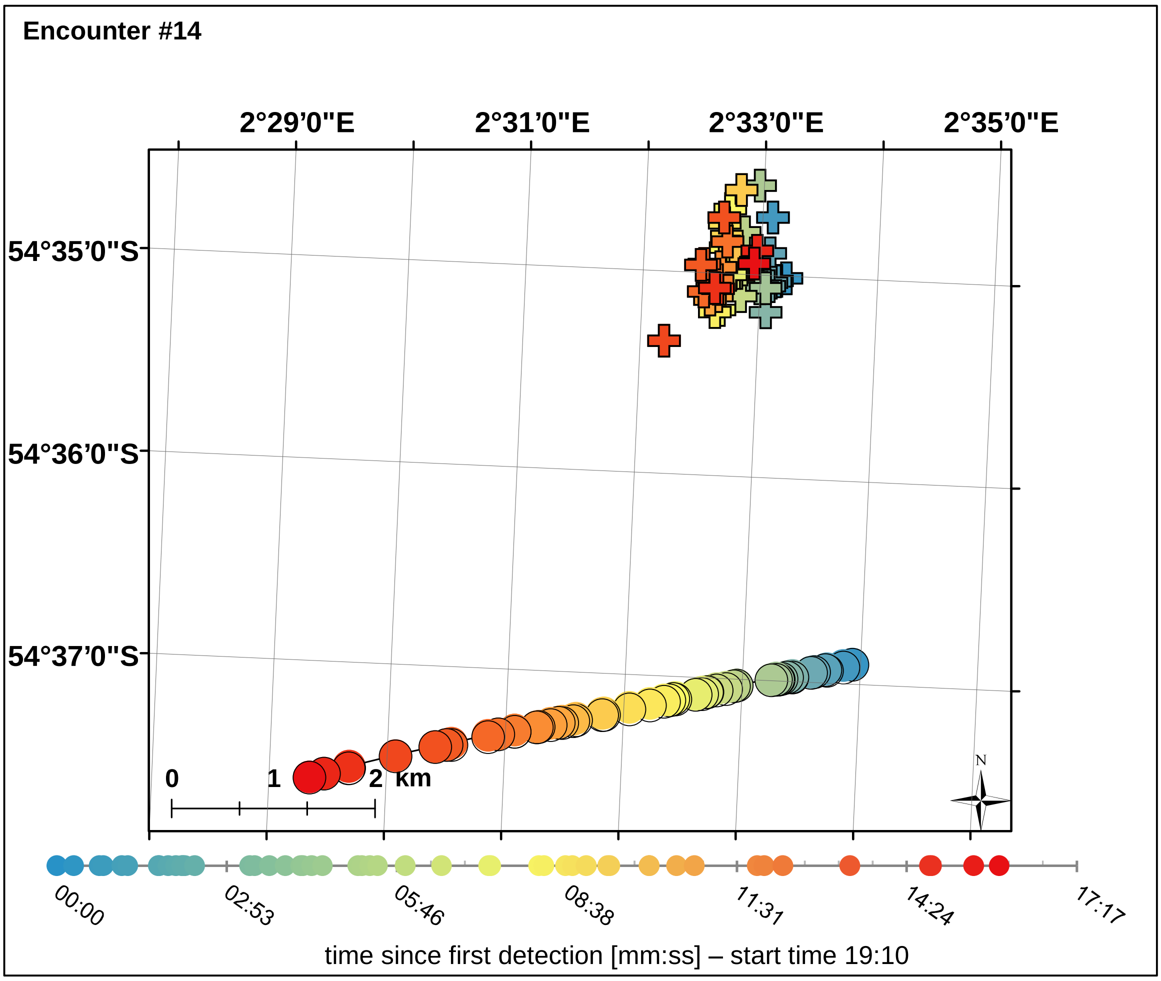

Fig. 43: Geo-referenced map of encounter #14, fin whales, 15:58.

A pod of three fin whales was detected at a distance of about 4000 m at ~90°. As *Polarstern* moved on the distance to the pod increased to ca. 6700 m until the pod was out of the range of the infrared camera. Over the course of 16 min the whales remained stationary.

Model #14

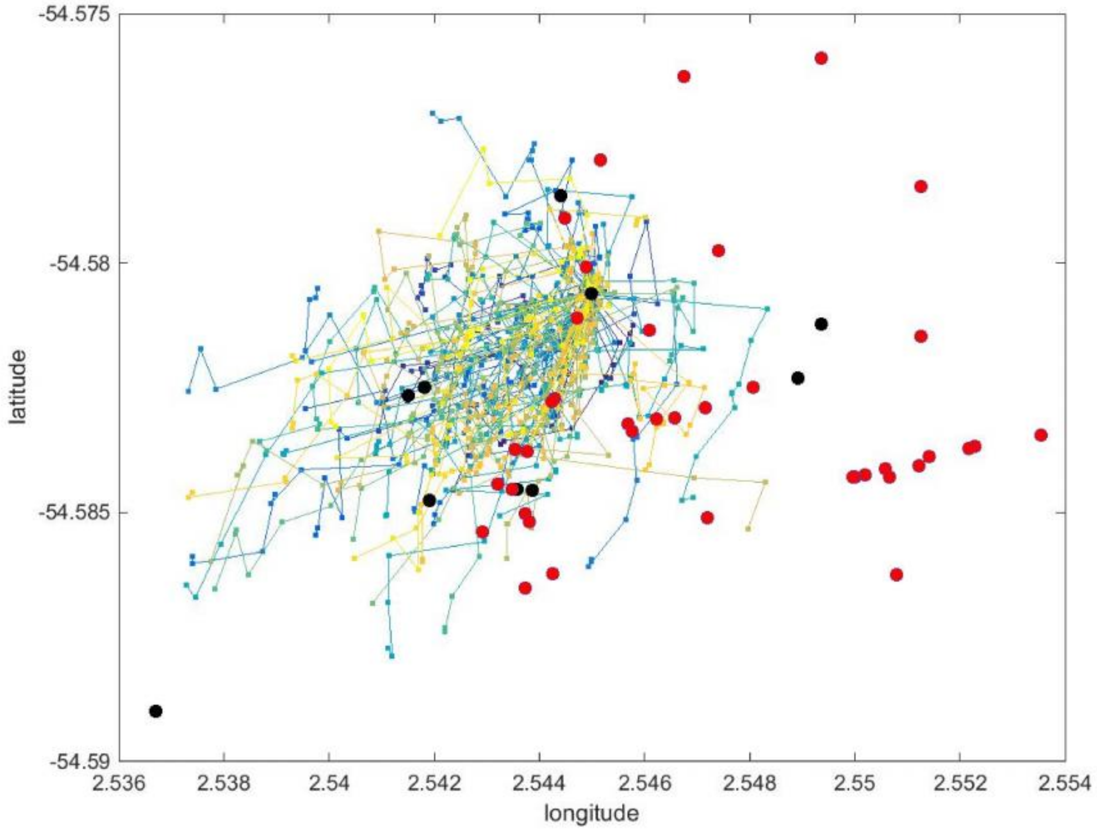

Fig. 44: Geo-referenced map of the model of encounter #14.

Even though not all events are covered by the model, there is a general consistency. The stationary behaviour of the pod is reflected by the modelled events.

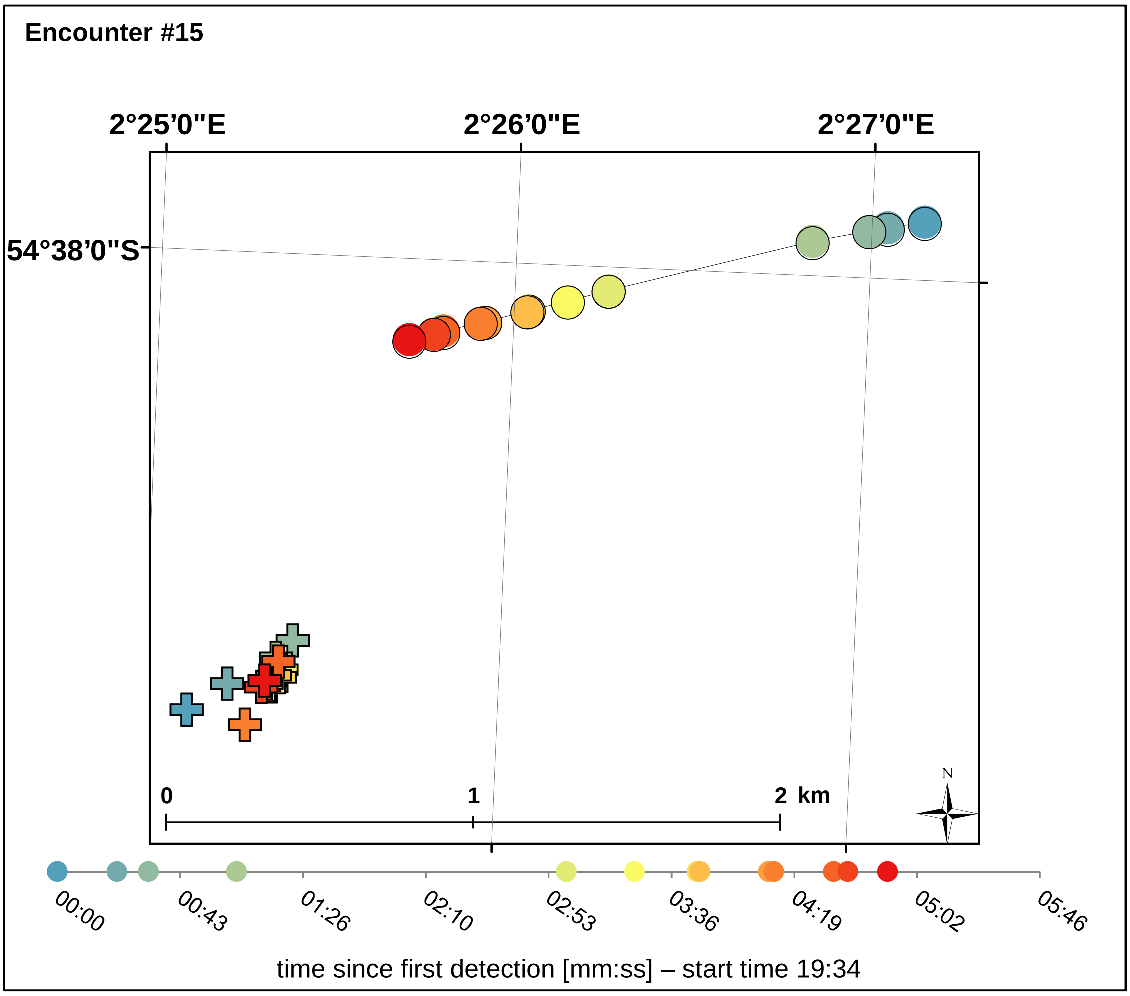

Fig. 45: Geo-referenced map of encounter #15, humpback whales, 4:52.
Two humpback whales were detected at an angle of approx. 25° at about 2500 m distance. *Polarstern* approached the whales to a distance of ca. 1200 m, increasing the angle to approx. 50°. During this time, the whales stayed in the same area without moving away.

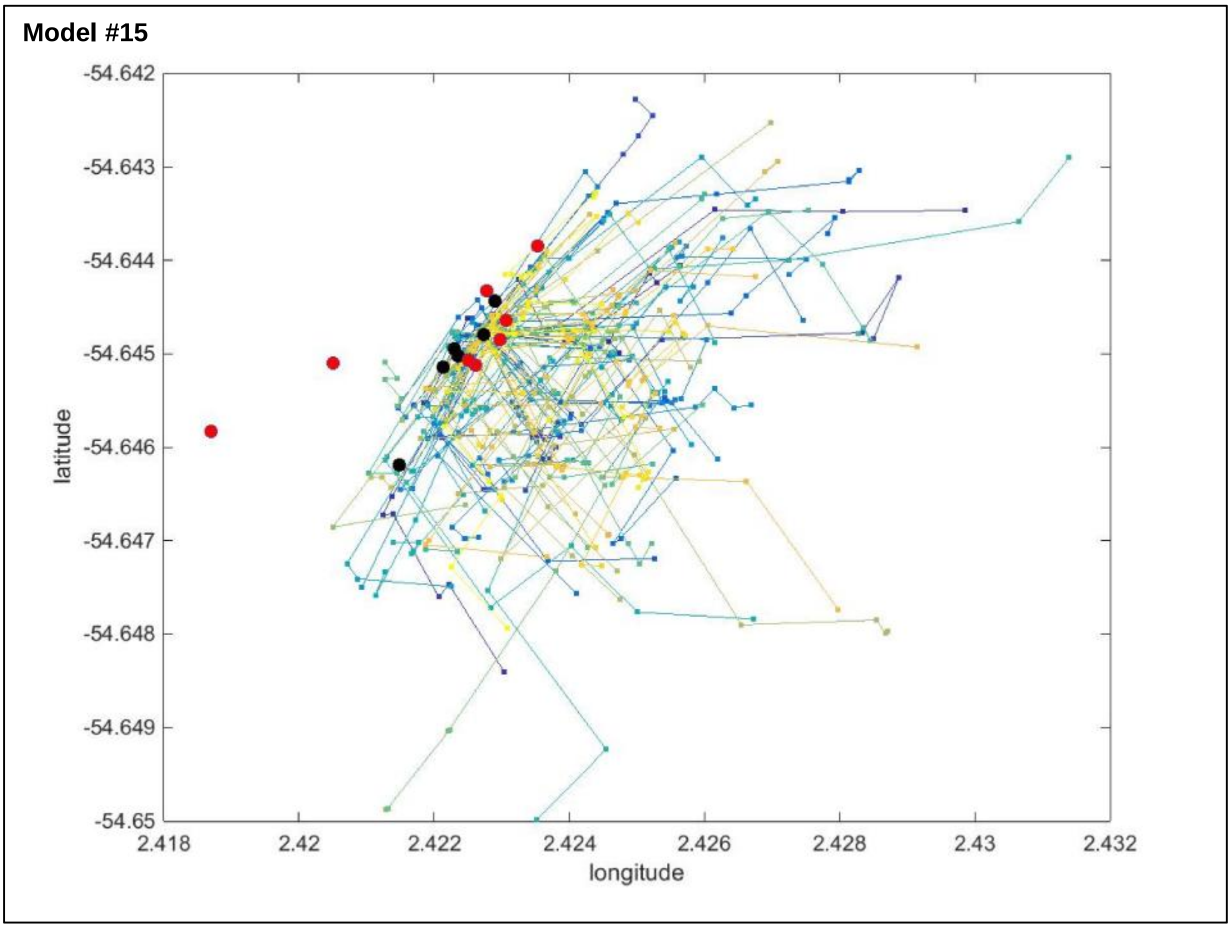

Fig. 46: Geo-referenced map of the model of encounter #15.

The events detected in the end of this encounter are covered up by the modelled events. The pod appears less stationary in the model.

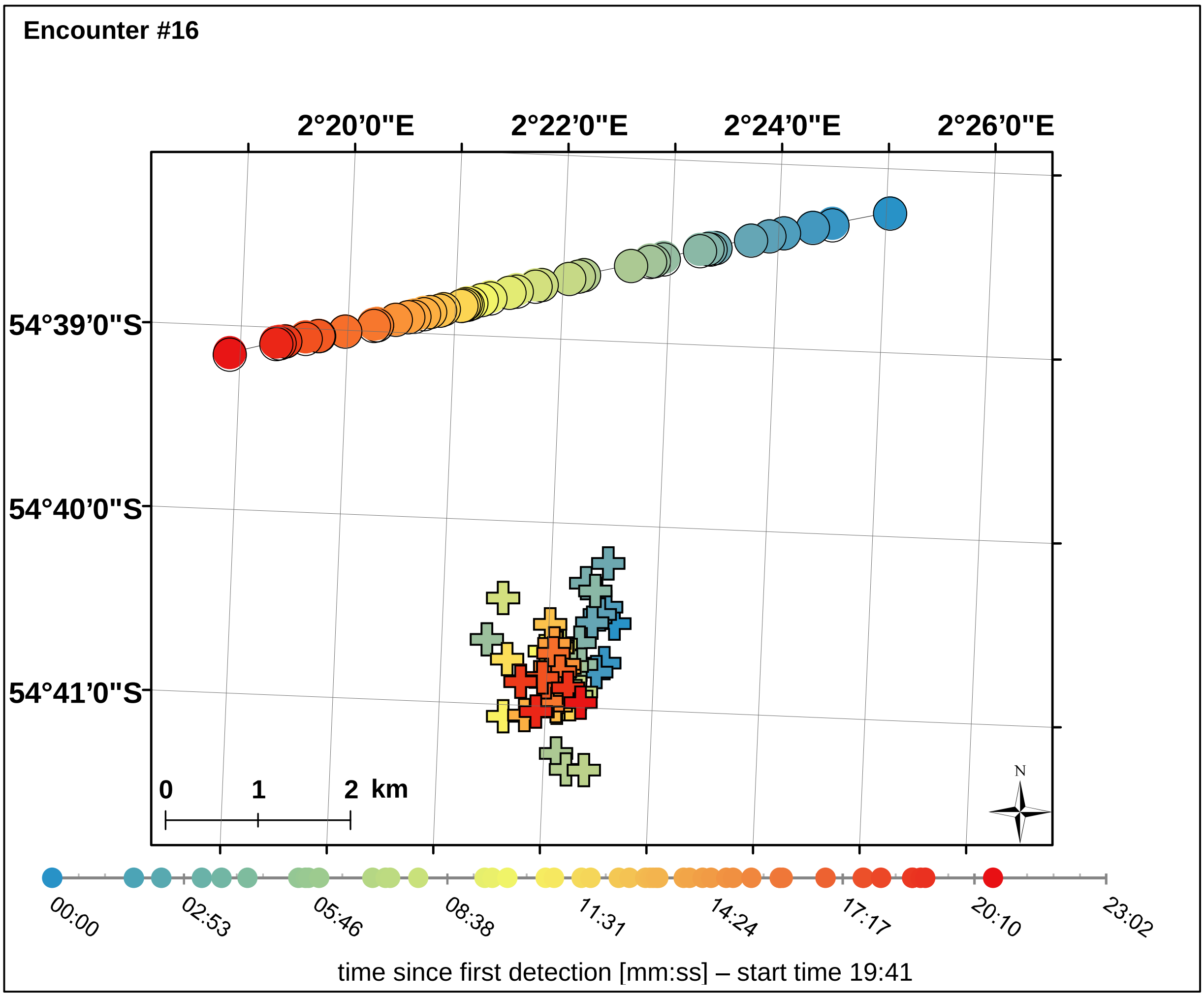

Fig. 47: Geo-referenced map of encounter #16, humpback whales, 20:34.
A pod of six humpback whales was detected at an angle of 45-55° in a distance of >5000 m. *Polarstern* passed by the pod and moved away while the whales did not move away but appeared rather stationary. During the encounter, no whale was sighted closer than ~3600 m.

Model #16

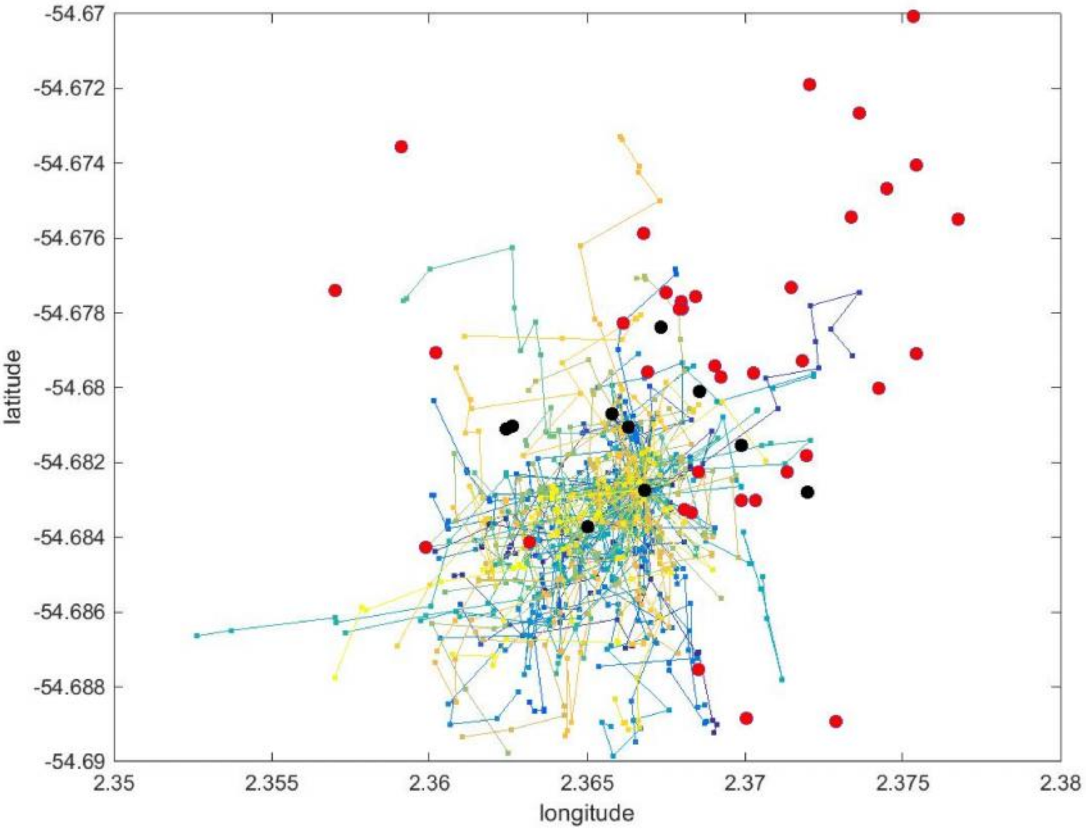

Fig. 48: Geo-referenced map of the model of encounter #16.

The model of the encounter coincides with the events detected in the thermal images. Both the detected events and modelled events show a virtually stationary pod.

The behaviour of the focal pods in the encounters #3 (Fig. 49), #6 (Fig. 50), and #9 (Fig. 51) is not clearly recognizable. All of the pods were tracked at angles >86° and in distances of >2500 m. Additionally, they were rather short (~1-10 min) and only a few events (9-10) were detected making it difficult to define whether the animals were traveling or remaining in the area. Models of encounter #3, #6, and #9 could not be generated due to the low number of events that the models could be based on.

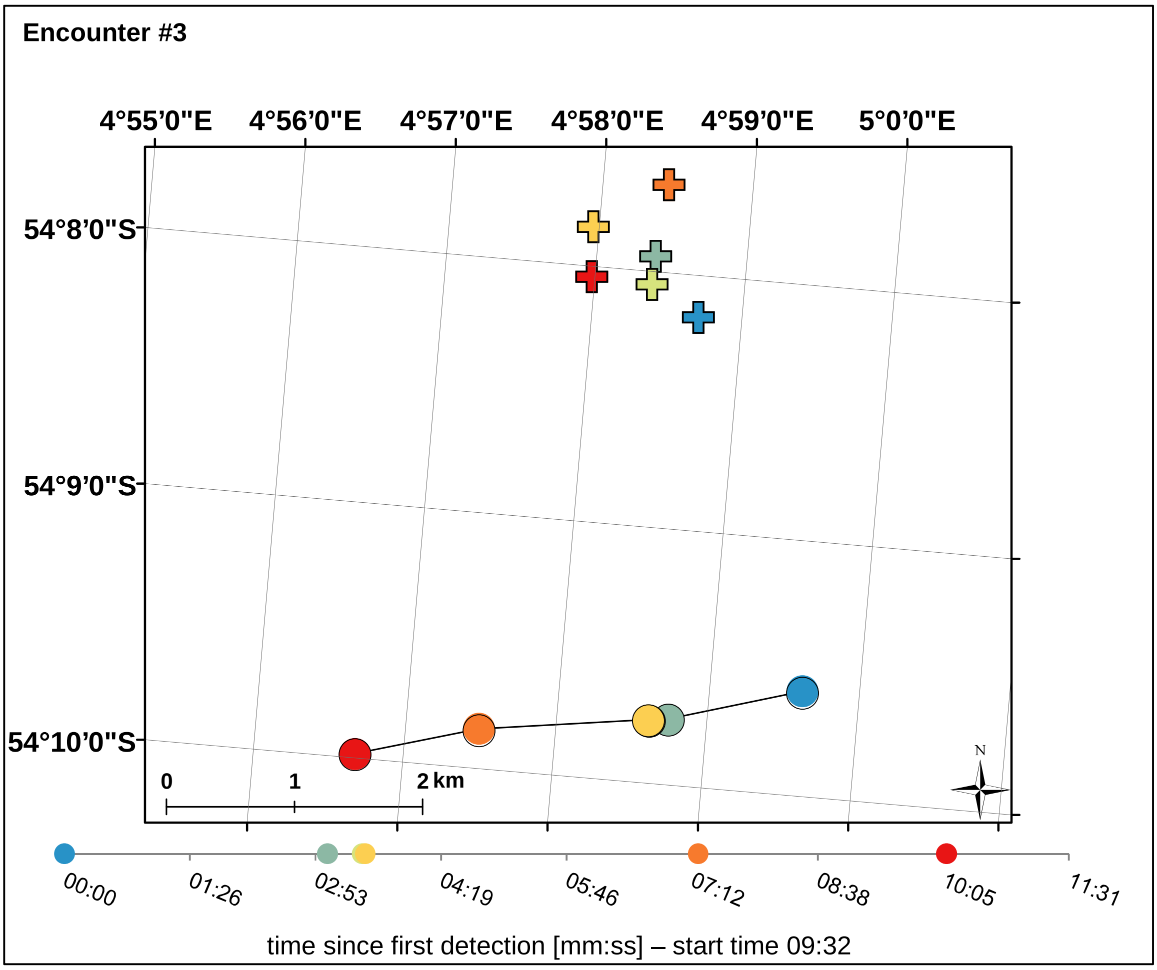

Fig. 49: Geo-referenced map of encounter #3, unidentified species, 10:07.
Two whales were observed in a distance of 3000-4500 m from the ship. No clear orientation is recognizable.

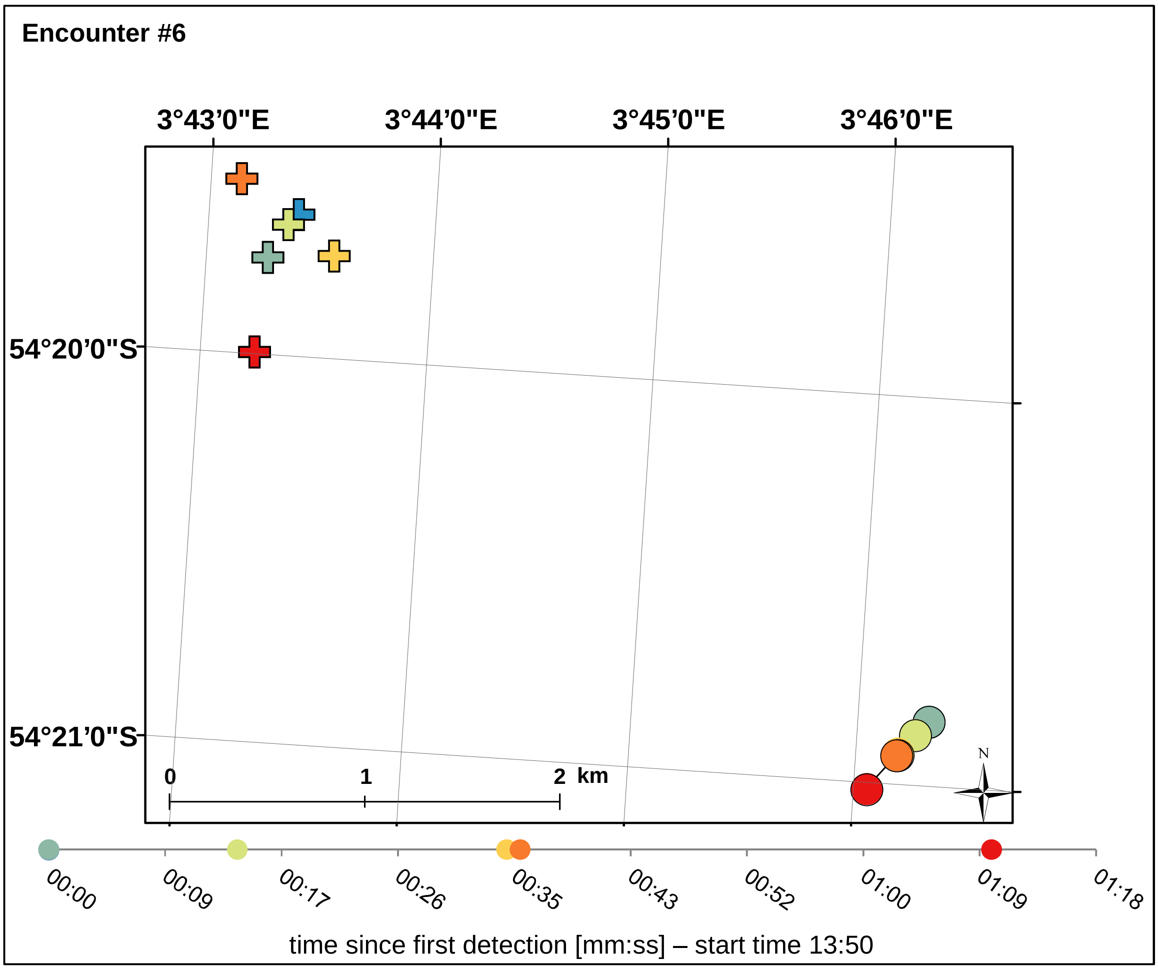

Fig. 50: Geo-referenced map of encounter #6, unidentified species, 1:10.
A pod of four whales was detected in a distance ranging from 3860 and 4480 m. During this short encounter, no clear orientation of the pod was recognizable.

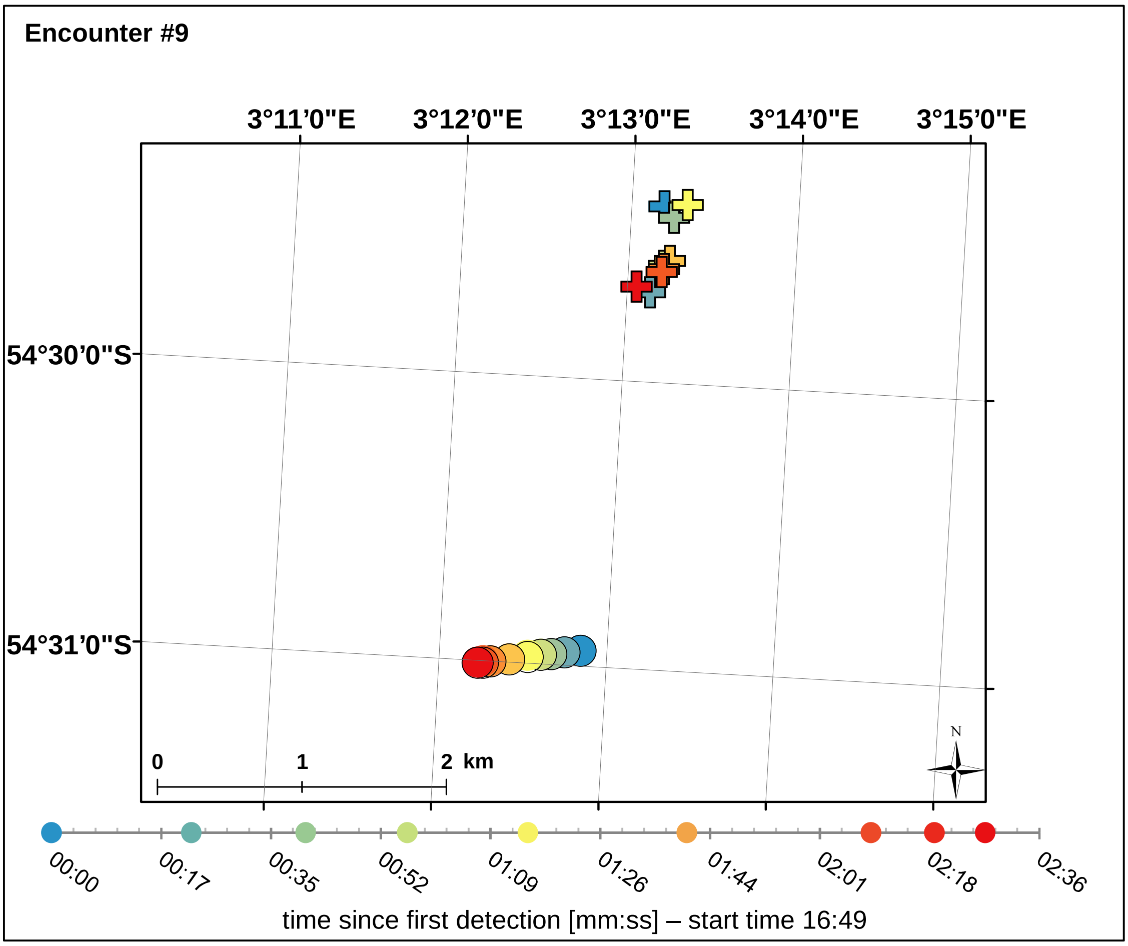

Fig. 51: Geo-referenced map of encounter #9, unidentified species, 2:27.
A pod of three humpback whales was observed in a distance ranging from 2570 to 3320 m at angles ranging from ~107-121°. Over the course of this short encounter, the whales appeared rather stationary.

Fig. 52 shows the number of encounters during which behavioural responses of the focal pods were detected and the encounters without a reaction or with undefined behaviour. The encounters are categorized according to the minimum distance in which the focal pod was detected from *Polarstern* during each encounter. During three of the four encounters that took place within 1000 m of, a behavioural response was observed (#2, #7.1, #7.2). Encounter #8 was the only pod that was observed within 1000 m of the vessel without reacting to *PS*. In a distance of 1000 m to 2000 m, two focal pods displayed behavioural changes (#4, #5), while the other two pods did not show a reaction (#12, #15). The focal pods of the two encounters (#1, #9) that took place between 2000 m and 3000 m distance from *PS* did not appear to show a behavioural response. The majority of the encounters occurred in the range from 3000 m to 4000 m from the ship (#3, #6, #10, #11, #13, #14, #16). None of these pods responded behaviourally to *PS*. Behavioural responses were seen in both fin (#4, #5) and humpback whales (#7.1, #7.2).

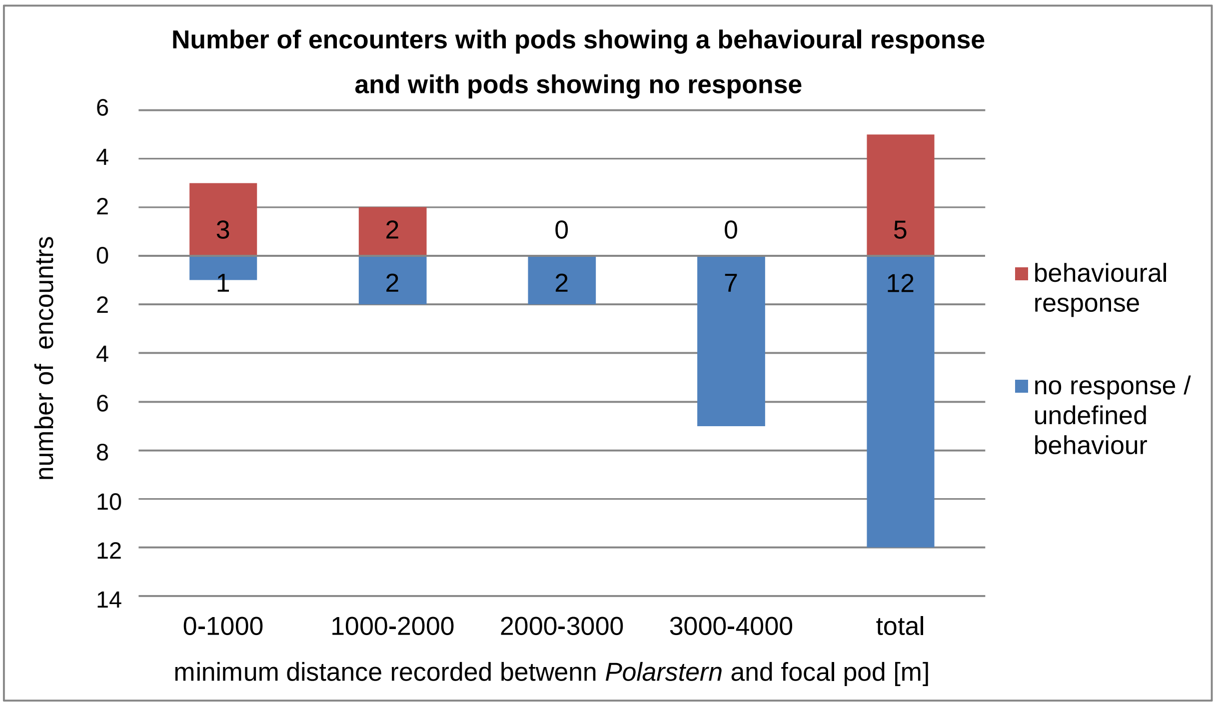

Fig. 52: Overview of the numbers of encounters with a behavioural response of the focal pod and with pods showing no response or undefined behaviour to *Polarstern* divided by the minimum distance in which a whale from the focal pod was detected during each encounter. Red bars indicate the numbers of encounters with observed behavioural reactions, blue bars indicate the number of encounters during which no response of the focal pod was observed or the behaviour could not be defined. Three of the four focal pods observed within 1000 m of the ship showed behavioural responses. In the range from 1000 to 2000 m, two pods showed no response and two pods showed a behavioural response. Two more pods were observed between 2000 and 3000 m, and seven pods between 3000 and 4000 m. In none of these pods a behavioural response was found.

4.2 Comparison of thermal imaging based and visual whale detection

For encounter #11 no visual data was available due to lack of distance estimation by the MMOs and, therefore, this encounter was excluded from the behavioural analysis. However, the number of events was recorded for all encounters. Since the visual observers assumed to follow only one pod during encounter #7, the encounters #7.1 and #7.2 were combined as #7 resulting in 16 encounters.

4.2.1 Number of detected events and estimated number of animals in the focal pod

During the entire observation time, 955 events were detected in the thermal video streams which is ~1.5 times the number of events detected by the visual observers who recorded a total of 638 events (Fig. 53, Tab.7). More events were detected visually than in the thermal stream during the encounters #3 (Fig. 57), #5 (Fig. 59), #7 (Fig. 61), #9 (Fig. 63) and #10 (Fig. 64). During the remaining 11 encounters, up to 2.6 as many events were detected in the thermal video stream.

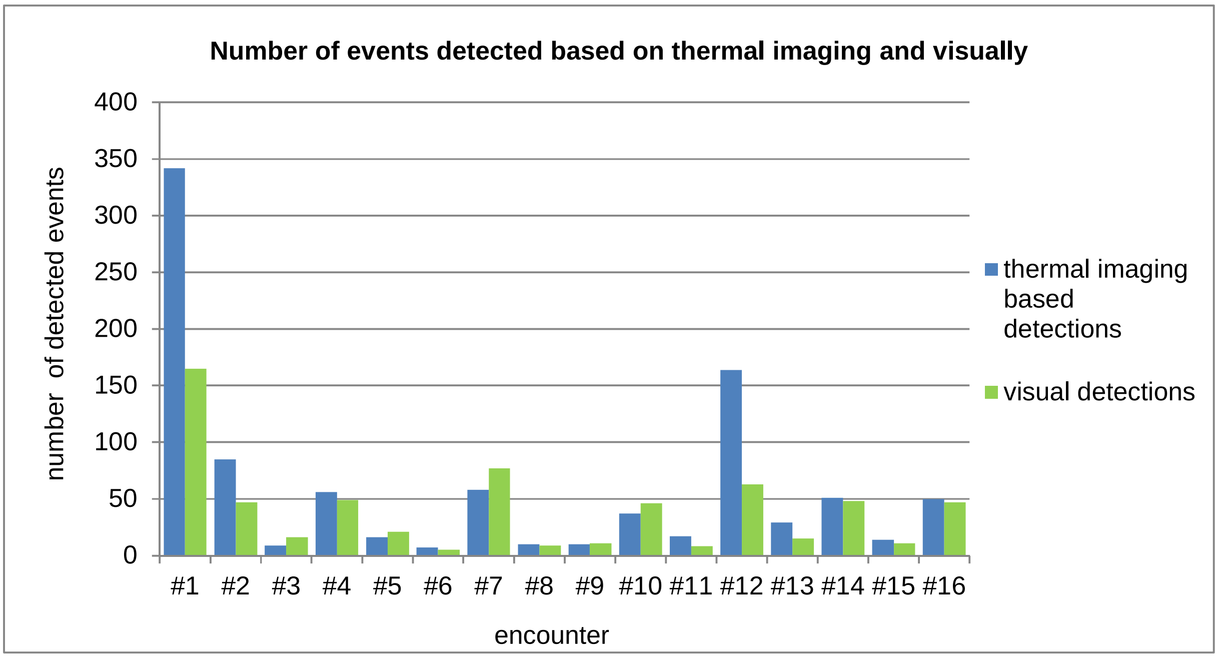

Fig. 53: Number of events detected based on thermal imaging and detected visually for each encounter. In 5 of the 16 encounters, more events were detected by the visual observer than in the thermal video stream. All events that were detected within one second in the thermal images were counted as seen by the visual observers since they could only record one blow per second. During 5 encounters, more events were detected visually than in the thermal images; during the other 11 encounters, the number of blows detected in the thermal images is higher. In total, 955 events were detected in the thermal images, ~1.5 as many events as the visual observers who recorded 638 blows.

Additionally, the number of animals was underestimated by the visual observers in seven encounters (Tab.7); for two encounters, they did not give an estimation, and in the remaining seven encounters the estimation was the same.

Tab. 7: Number of events detected by the visual observers and based on the thermal images and the number of animals estimated by the each detection method.

Encounter	Number of events detected based on thermal imaging	Number of events detected by MMOs		Minimum number of whales in focal pod estimated based on thermal recordings	Number of whales in focal pod estimated by MMOs
		Number of events recorded by the MMOs	Events recorded by the MMOs plus events detected within 1 sec in the thermal images		
#1	342	130	165	8	2-5
#2	85	39	47	6	2-4
#3	9	16	16	2	2
#4	56	47	49	5	2-3
#5	16	21	21	2	1-2
#6	7	4	5	4	n/a
#7	58	76	77	4	2-3
#8	10	9	9	2	2
#9	10	11	11	2	n/a
#10	37	46	46	4	3-4
#11	17	8	8	4	3
#12	164	58	63	4	1-4
#13	29	15	15	3	1-2
#14	51	45	48	3	1-3
#15	14	10	11	2	1-2
#16	50	46	47	6	1-3
total	**955**	**573**	**638**		

4.2.2 Thermal imaging based and visual distance estimation

There was a significant difference in the distance estimations between the detection methods for distances between 1000 and 6000 m. Over all distances, the estimations made by the visual observers exceed the distances calculated based on the thermal images (Fig. 54). The difference between the estimations is increasing with increasing distance between *PS* and an event. For instance, events that were sighted at an average distance of 2554.01 m (SD 303.65 m) in the thermal stream were estimated at an average of 3372.37 km (SD 1116.49 m) by the visual observers; events detected at an average distance of 4597.21 m (SD 264.93 m) in the thermal recordings were estimated to be approx. 2000 m further away by the MMOs (mean 6586.98, SD 1581.03). For events detected within 1000 m and at distances greater than 6000 m from the ship, the estimations are similar.

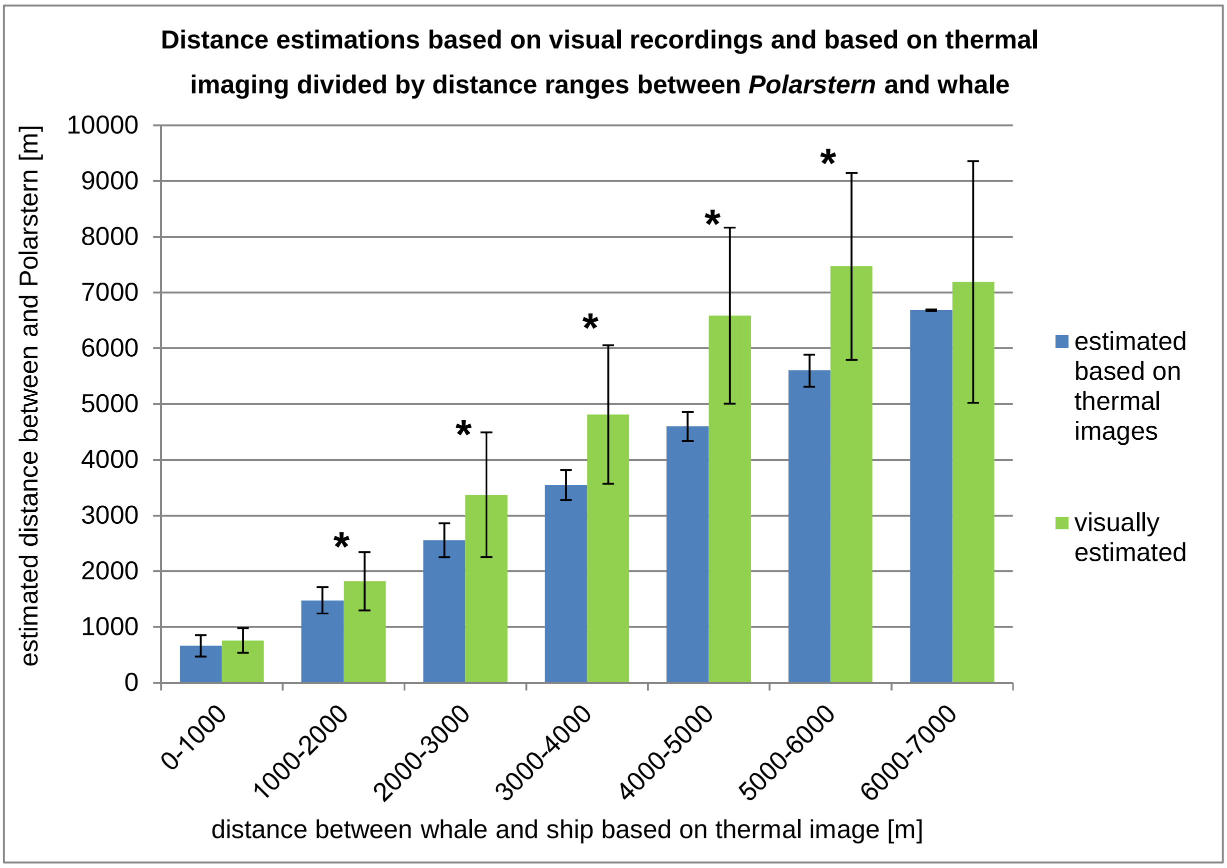

Fig. 54: Mean distance estimations from the thermal images (blue bars) and from the visual observers (red bars) categorized according to the distance between the detected event and *Polarstern* in ranges of 1000 m. The visual estimations exceed the distances based on the IR recordings independent of the distance of the detected event. The difference between the estimations increases with increasing distance of the event. For events detected within 1000 m from the ship, the estimations are similar, while at distances between 4000 m and 5000 m based on the thermal images the visual observers estimated the events at ~6500 m. Asterisks indicate significant differences (p-value < 0.0001).

Both visual and thermal imaging based whale detection was still possible at mean wind speeds of up to 24 kn and, consequently, in high sea states. Throughout the data collection the visibility was above 10000 m and was not restricted by precipitation.

4.2.3 Comparison of the behavioural analysis

Encounter #2 (Fig. 56) is the only encounter during which the behavioural response of the focal pod was detected both in the thermal stream and visually. The observers recorded the first shift in the orientation to a direction perpendicularly to *Polarstern*'s path and also the second change in direction away from the vessel. In the thermal stream, a second pod further away from *PS* was also recorded.

The behavioural response of the focal pods in #4 (Fig. 58) and #5 (Fig. 59) is not recognizable in the visual recordings. The events are more dispersed than the thermal imaging based events and the pods do no show a clear orientation. During #5, the pod appeared to make a circular movement and move away from the ship's path in the end of the encounter.

During encounter #7 (Fig. 61), the visual observers thought to follow a single pod, while the events detected in the thermal images show two different pods. The direction change of the first pod was not recorded by the MMOs and the behavioural response of the second pod is also not noticeable. The events detected visually are more dispersed making it difficult to define the behaviour.

The events detected visually during encounter #13 (Fig. 66) are also spread more widely compared to the thermal imaging based detections, and the distances of the whales seem overestimated. However, the visual observers thought to follow a second pod during the end of the encounter (orange-red events). Due to the close proximity of the events that were detected in the thermal images the events appear to be belong to the same pod. Another pod traveling to the opposite direction of *Polarstern*'s heading and closer to her was detected both by the visual observers and in the thermal images.

In many of the other encounters, the visually recorded events are also more dispersed and the distances seem overestimated by the visual observers. During encounter #3 (Fig. 57), they detected events ~4 min earlier than the thermal imaging based detections. The whales appeared to move away from *Polarstern*'s path, while they seemed rather stationary based on the thermal images. The recordings of encounter #9 (Fig. 63) seem similar but three events were estimated at considerable greater distances (>6000 m) than the rest of the events (approx. 3730 m) and the events detected in the thermal images (2570-3530 m). In #6 (Fig. 60), the angle between *PS* and the focal pod differs by ca. 40° between in the visual recordings and the thermal imaging based recordings. Additionally, the visually detected events were recorded in a distance of 3740-6230 m while they were recorded at 2400-4490 m in the thermal images.

The behaviour of the focal pods in #8 (Fig. 62) and #10 (Fig. 64) were recorded both in the thermal images and by the visual observers. In #8, the movement of the focal pod towards *Polarstern* was recognized in both recordings even though the events detected visually were spread more widely. The focal pod during #10 appeared stationary in both recordings; however, some the distances of some events seemed overestimated by the visual observers. Similar, during encounter #15 (Fig. 68), the events were more dispersed and the pod seemed less stationary in the visually recordings than in the thermal imaging based recordings even though there is a general consistency.

Several pods were detected both visually and in the thermal images stream during encounter #12 (Fig. 65). The MMOs tracked a pod that was moving in the opposite direction of *Polarstern* in a distance of >9000 m and also recorded some closer events in the beginning and the end of the encounter. In contrast, the focal pod tracked in the thermal stream was swimming perpendicularly to *PS*'s path while she was passing by it. Additionally, blows from other animals were recorded.

In the thermal images of encounter #14 (Fig. 67), the focal pod appeared to remain in the same area throughout the encounter in a distance of approx. 2840-6690 m as *Polarstern* was approaching and passing by it. The visual recordings, in contrast, showed a pod of whales swimming in a semicircle more than 6000 m away with three events estimated at distances greater than 9000 m. Similar to this encounter, the MMOs recorded a pod swimming in a semi-circle in the opposite direction than the heading of *PS* during encounter #16 (Fig. 69). In contrast, the events detected in the thermal images show a stationary pod.

During encounter #1 (Fig. 55), a movement away from *PS*'s path towards the opposite direction is recognizable in the events detected visually and based on the thermal images. However, the MMOs estimated greater distances of some of the events and greater angles between *PS* and the whales.

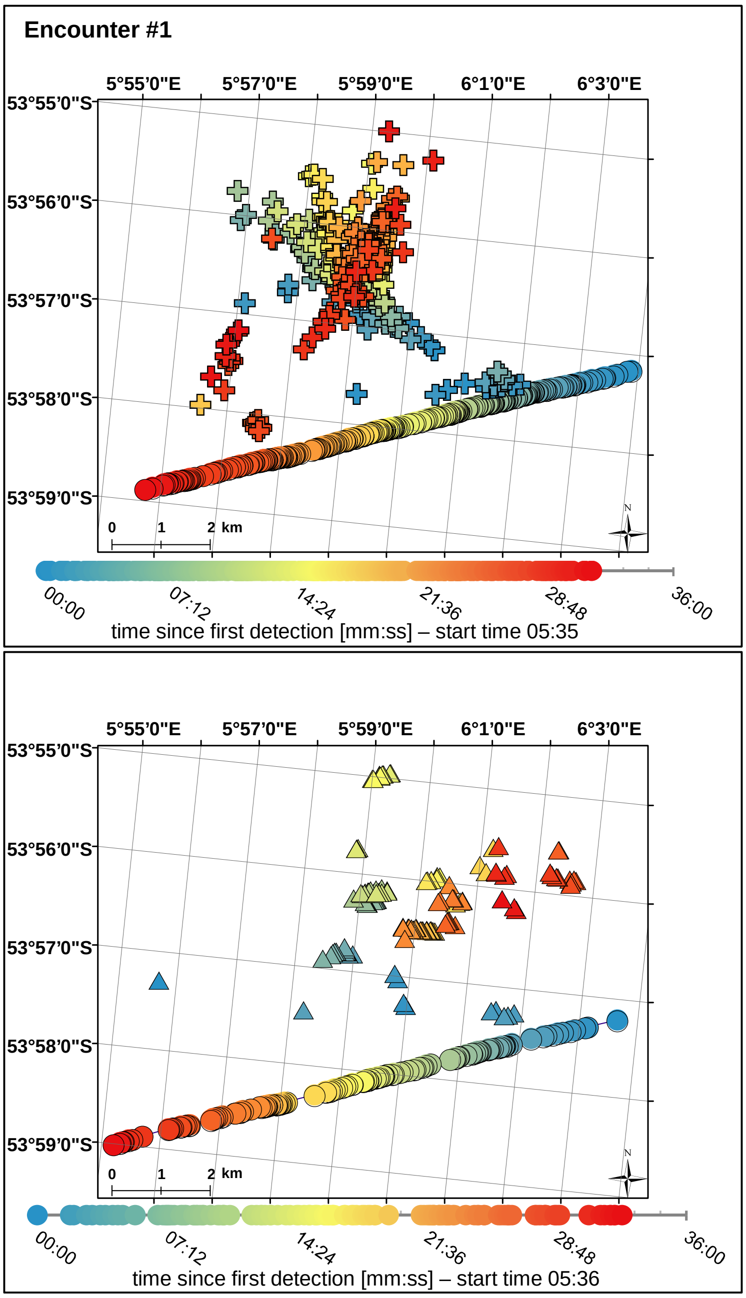

Fig. 55: Geo-referenced maps of encounter #1 based on thermal recordings (top; 342 events) and based on visual recordings (bottom; 130 events).

Coloured circles mark the route of *Polarstern*, coloured crosses (top) and triangles (bottom) mark the track of a pod of fin whales recorded in the thermal stream (top) and visually (bottom), respectively (each beginning with blue). Colour represents time, i. e. circles and crosses with the same colour mark *PS*'s position and a whale's position at the same time[5].

Several groups were detected both visually and in the thermal video stream. The overall movement of the focal pod towards the opposite direction of *PS* is recognizable in both data sets; however the visual observers overestimated the angle and the distance of some events.

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[5] This description applies to the figures 51-65.

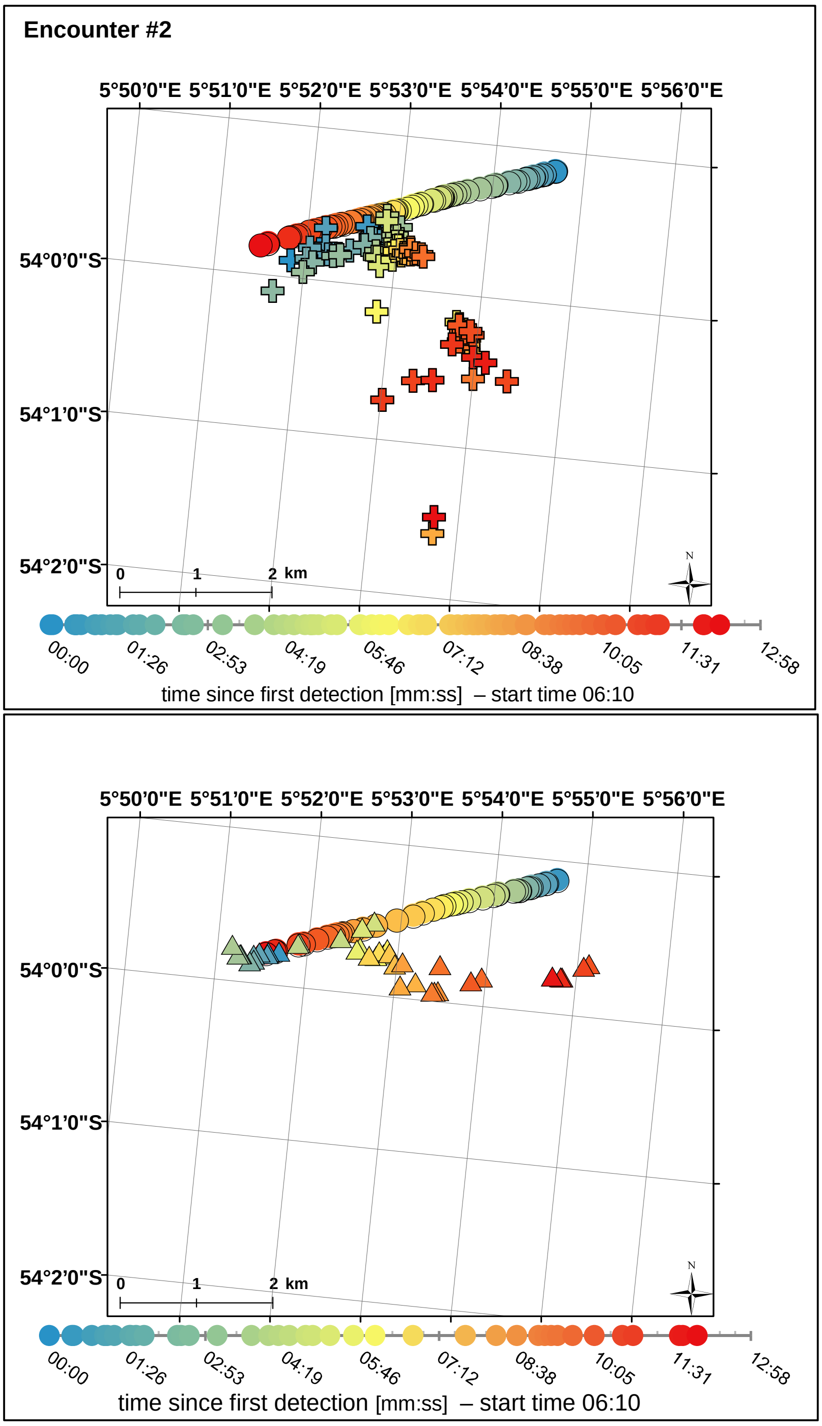


Fig. 56: Geo-referenced maps of encounter #2 based on thermal recordings (top; 85 events) and based on visual recordings (bottom; 39 events).

During this encounter, two different pods were recorded based on the IR recordings, while the visual observers recorded only one pod. The overall movement of the focal pod traveling away from *Polarstern* is recognizable from both data sets.

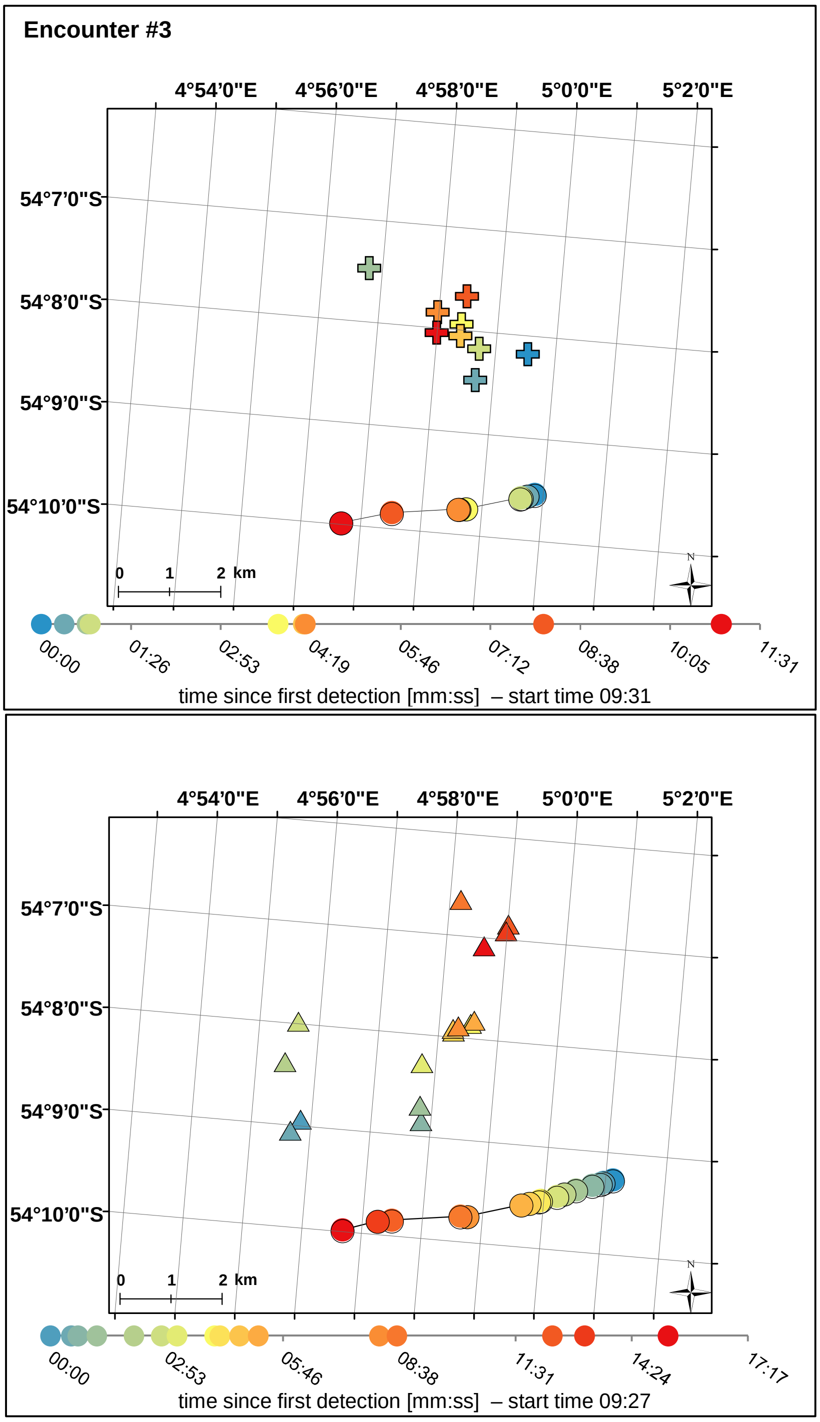


Fig. 57: Geo-referenced maps of encounter #3 based on thermal recordings (top; 9 events) and based on visual recordings (bottom; 16 events).

During the first four minutes of this encounter, the visual observers detected events that were not seen in the thermal video stream. Also, the observers saw several pods, and recorded whales swimming away from *Polarstern*'s path, while the whales seemed stationary in the IR recordings.

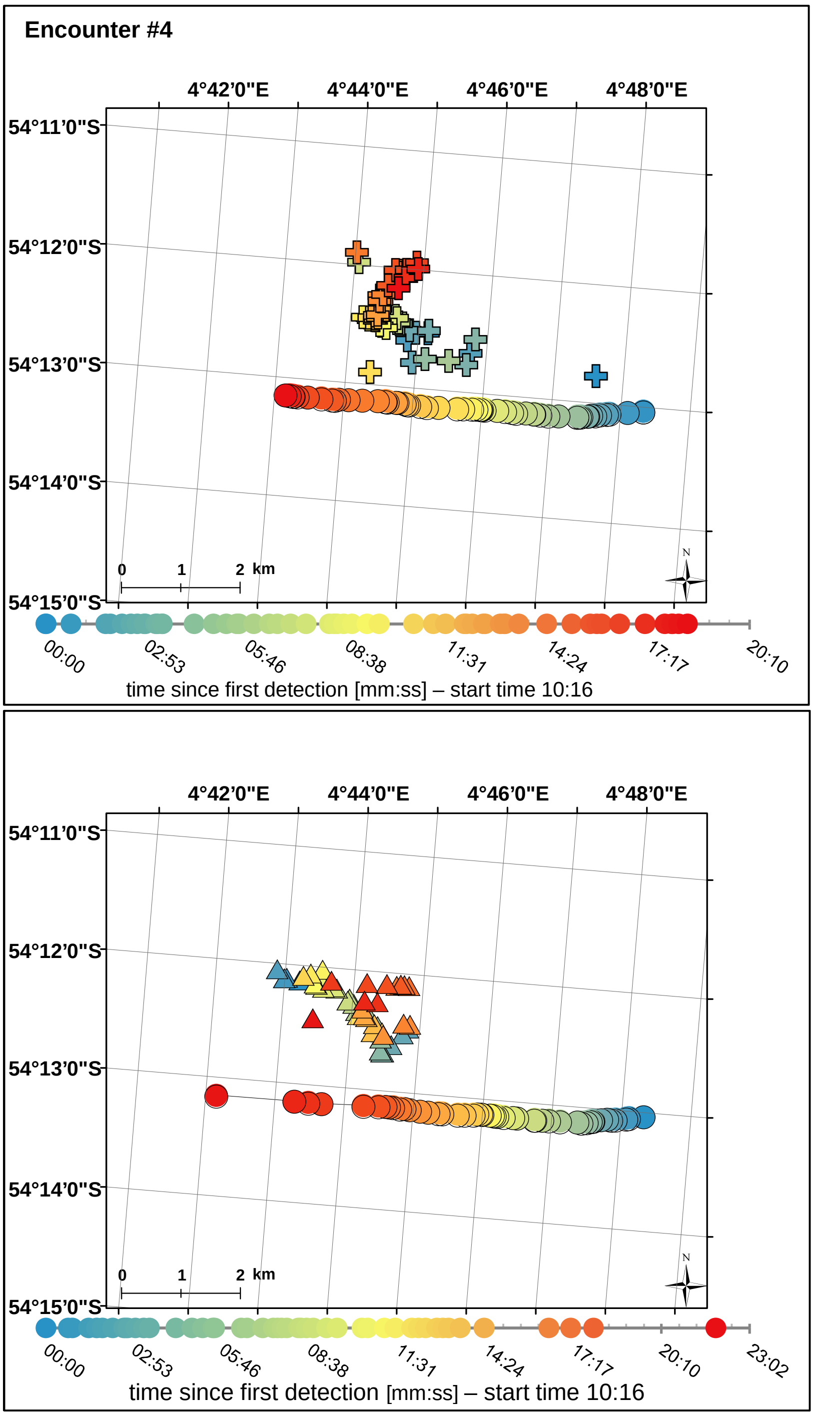


Fig. 58: Geo-referenced maps of encounter #4 based on thermal recordings (top; 56 events) and based on visual recordings (bottom; 47 events).
While in the IR stream the focal pod showed a shift in orientation from swimming parallel to *Polarstern*’s path to swimming away perpendicularly, no clear orientation towards a particular direction is recognizable according to the visual observers.

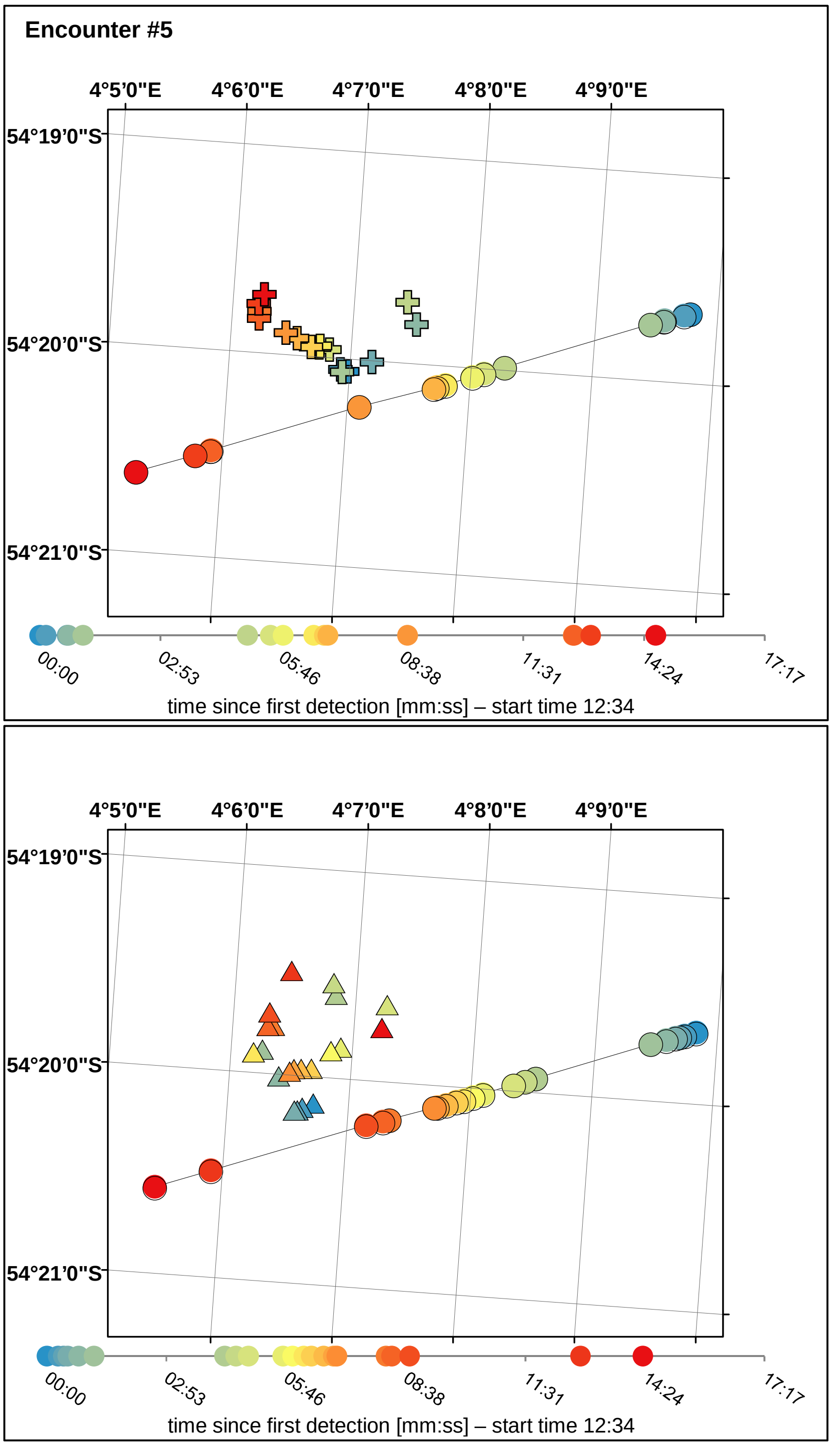


Fig. 59: Geo-referenced maps of encounter #5 based on thermal recordings (top; 16 events) and based on visual recordings (bottom; 21 events).

While the behavioural response of the fin whales is recognizable in the thermal recordings, no clear movement pattern was observed by the MMOs even though in the end of the encounter the whales were recorded to move away from *Polarstern*'s path.

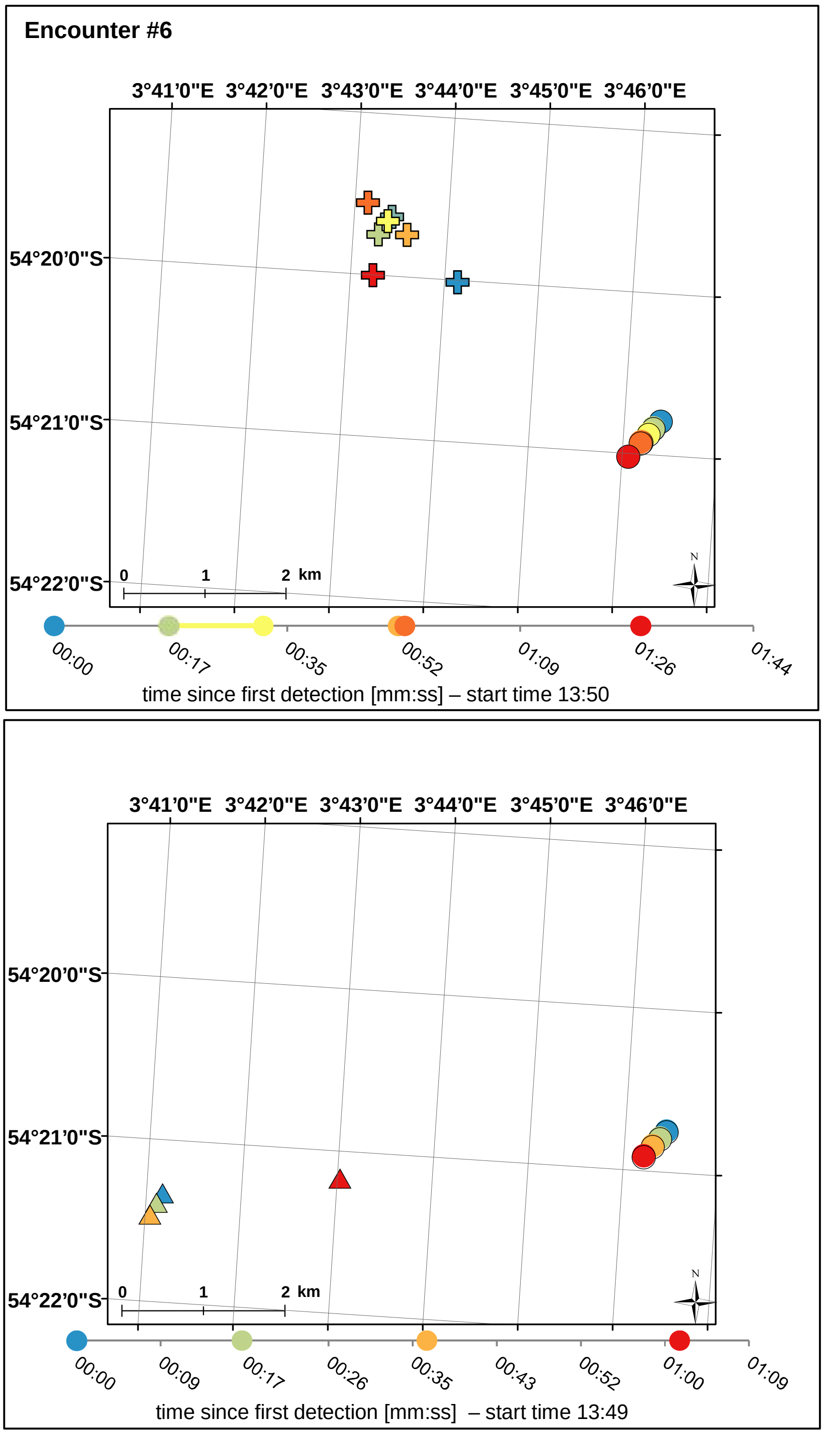
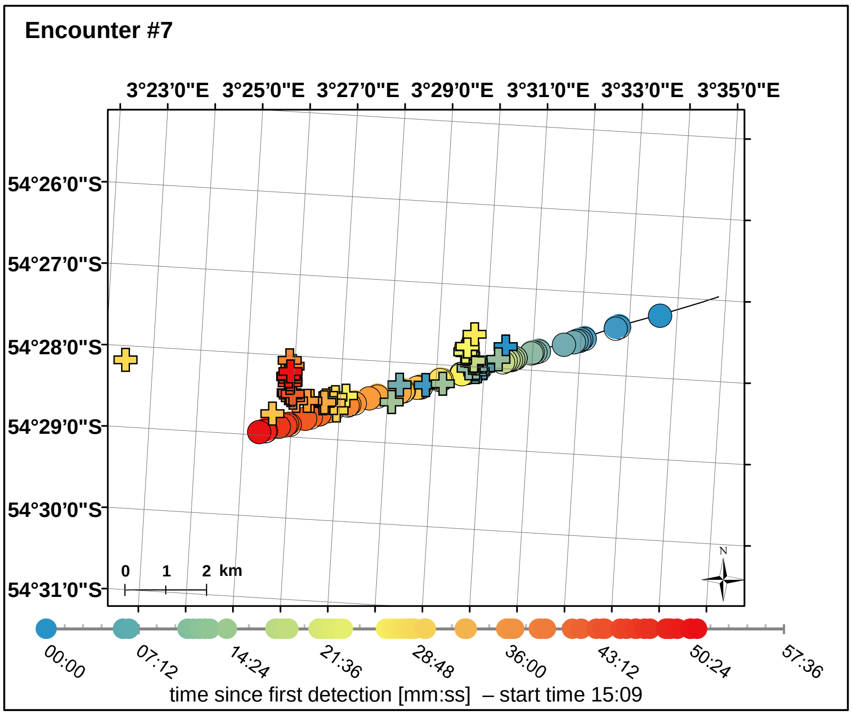


Fig. 60: Geo-referenced maps of encounter #6 based on thermal recordings (top; 7 events) and based on visual recordings (bottom; 4 events).

The bearing of the pods detected during this encounter differed by approx. 40° between the thermal imaging based recordings and the visual recordings. The short duration and the low number of events make difficult to determine the animals’ behaviour.



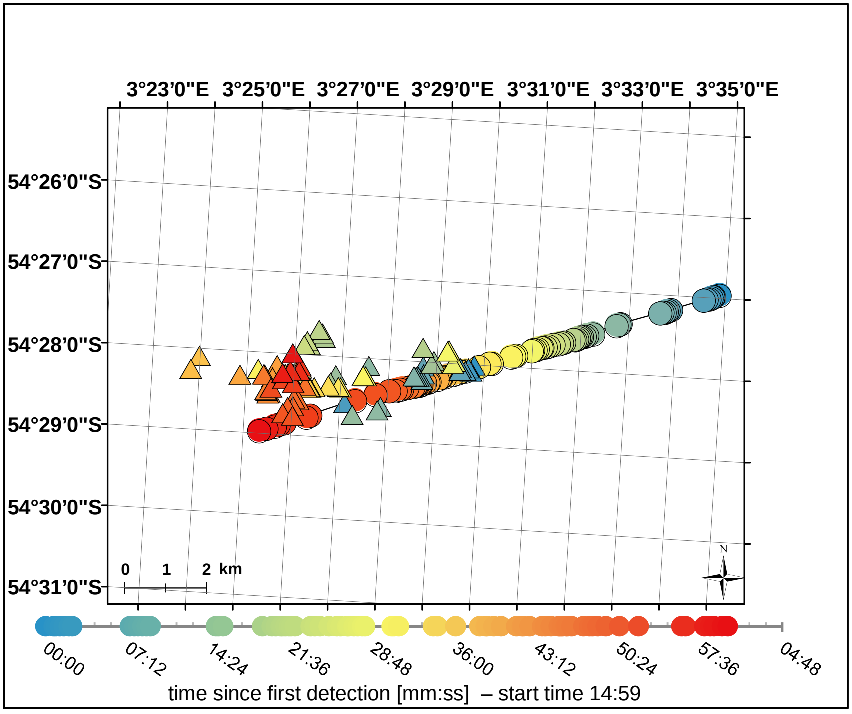


Fig. 61: Geo-referenced maps of encounter #7 based on thermal recordings (top; 58 events) and based on visual recordings (bottom; 76 events).

In contrast to the information from the MMOs, two pods were observed during this encounter and clearly distinguishable based on the thermal recordings. While behavioural responses from both pods were recognizable, no clear behavioural pattern is noticeable in the visual recordings. It seems that the visual observers often overestimated the distances between *PS* and an event.

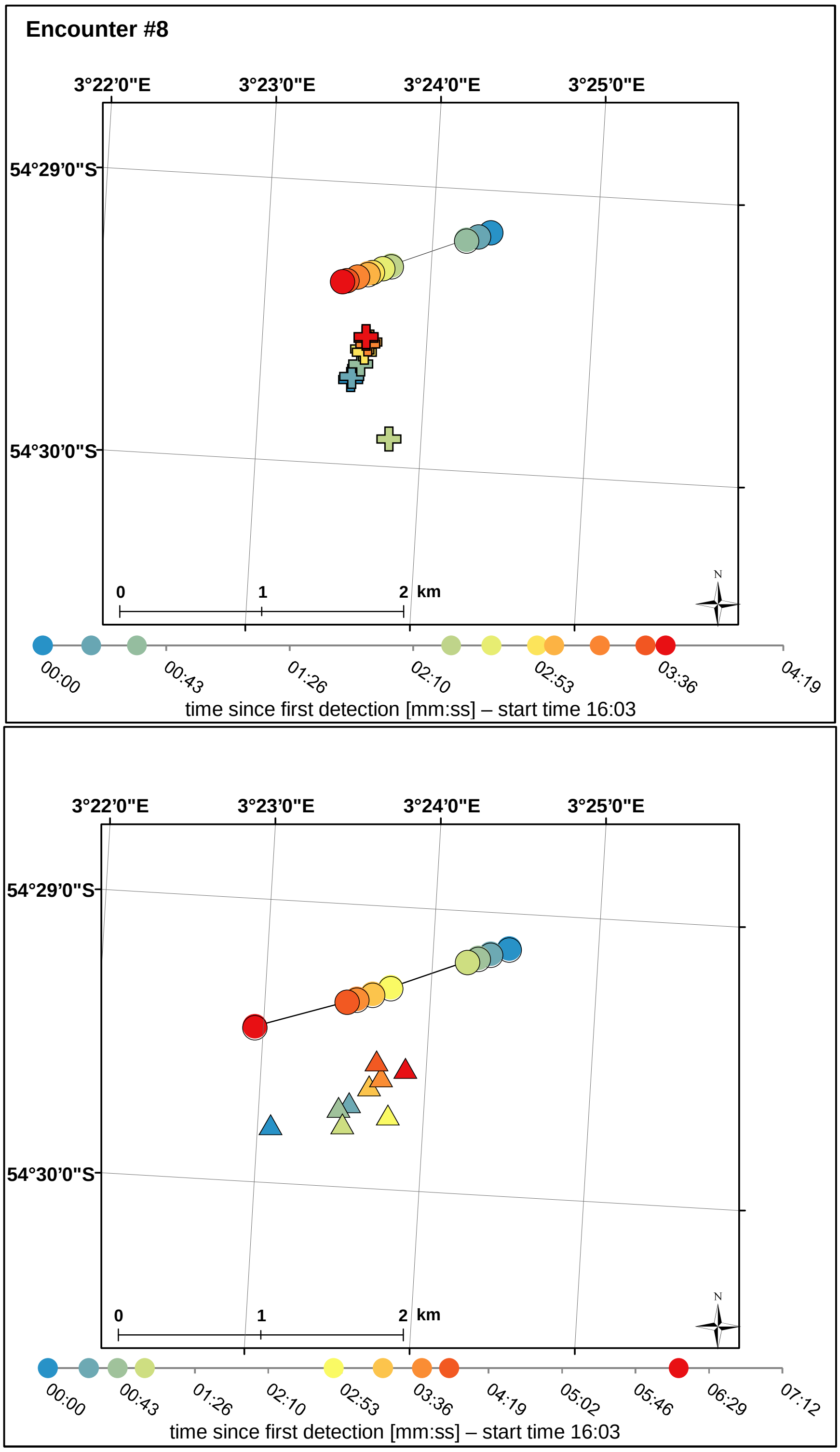


Fig. 62: Geo-referenced maps of encounter #8 based on thermal recordings (top; 10 events) and based on visual recordings (bottom; 9 events).

The recordings looked similar as the focal pod was observed to approach *Polarstern*'s path both in the thermal stream and by the visual observers, even though the pod's path is more clearly in the IR recordings. Additionally, in the thermal images another blow from a single animal was detected.

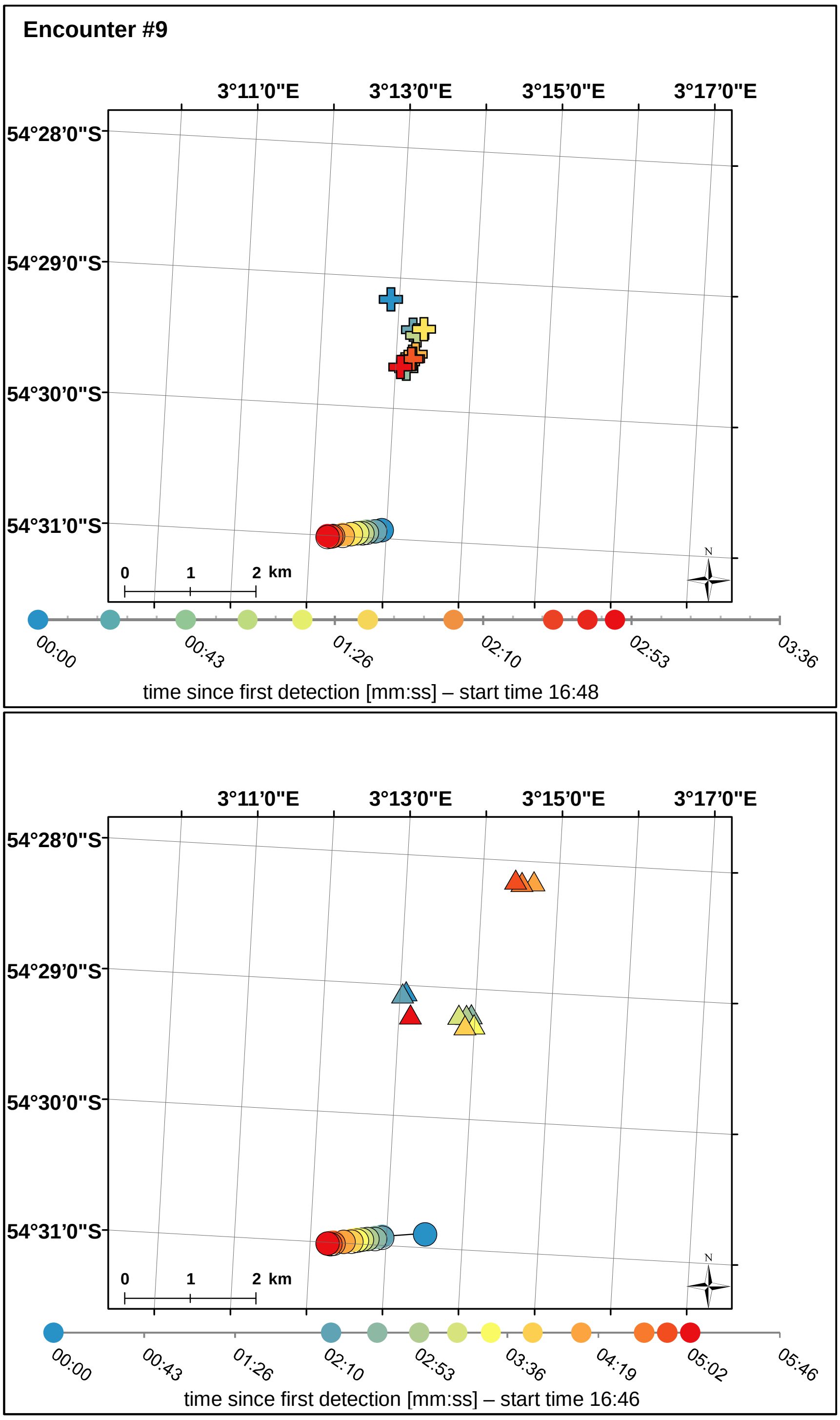


Fig. 63: Geo-referenced maps of encounter #9 based on thermal recordings (top; 10 events) and based on visual recordings (bottom; 9 events).
The visual observers recorded an event ~2 min earlier than the first thermal imaging based detection. The distance of some events which were detected both visually and in the thermal recordings was overestimated by the visual observers.

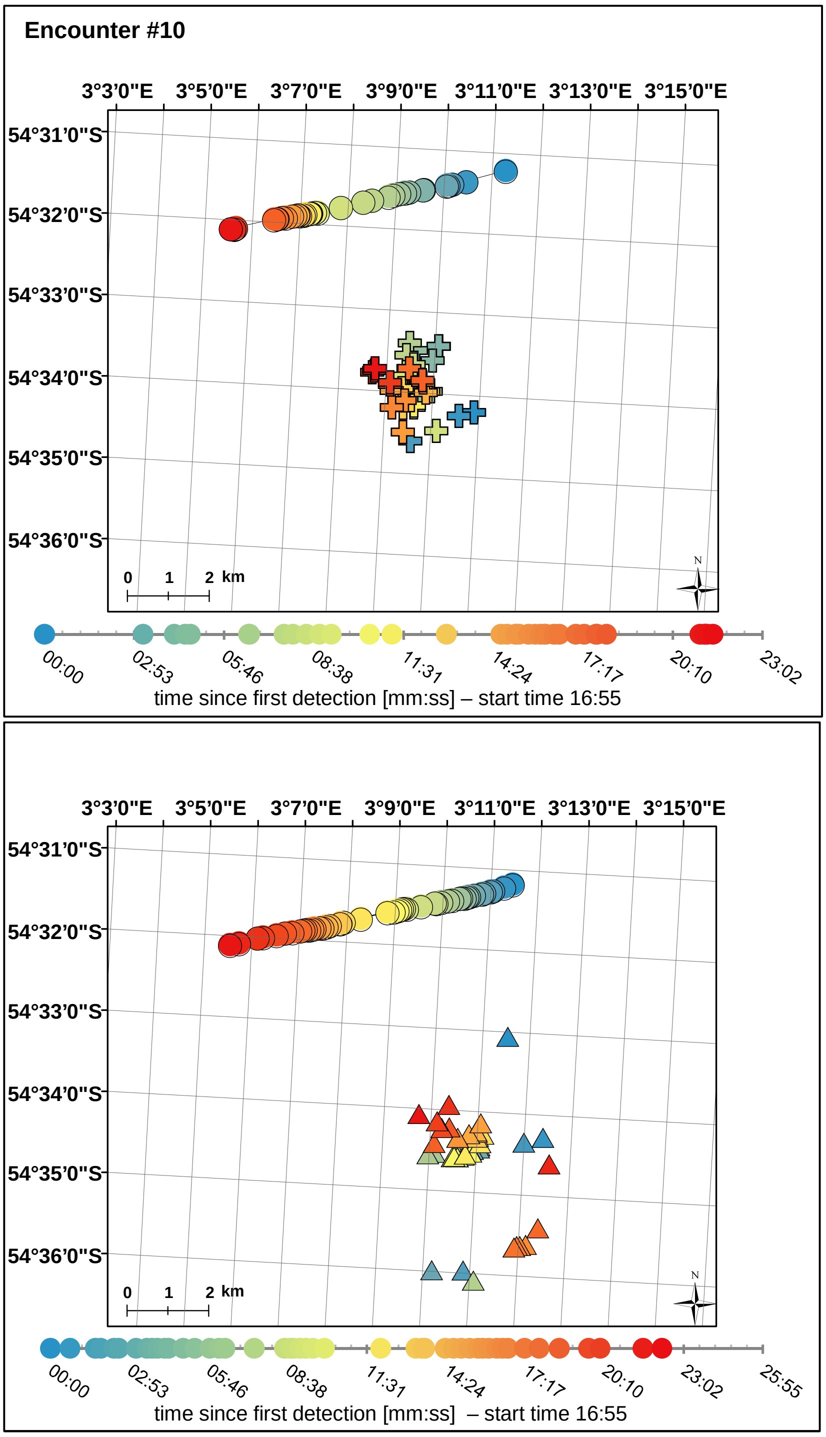


Fig. 64: Geo-referenced maps of encounter #10 based on thermal recordings (top; 37 events) and based on visual recordings (bottom; 46 events).

The visual observers recorded an event ~2 min earlier than the first thermal imaging based detection. The distance of some events which were detected both visually and in the thermal recordings was overestimated by the visual observers.

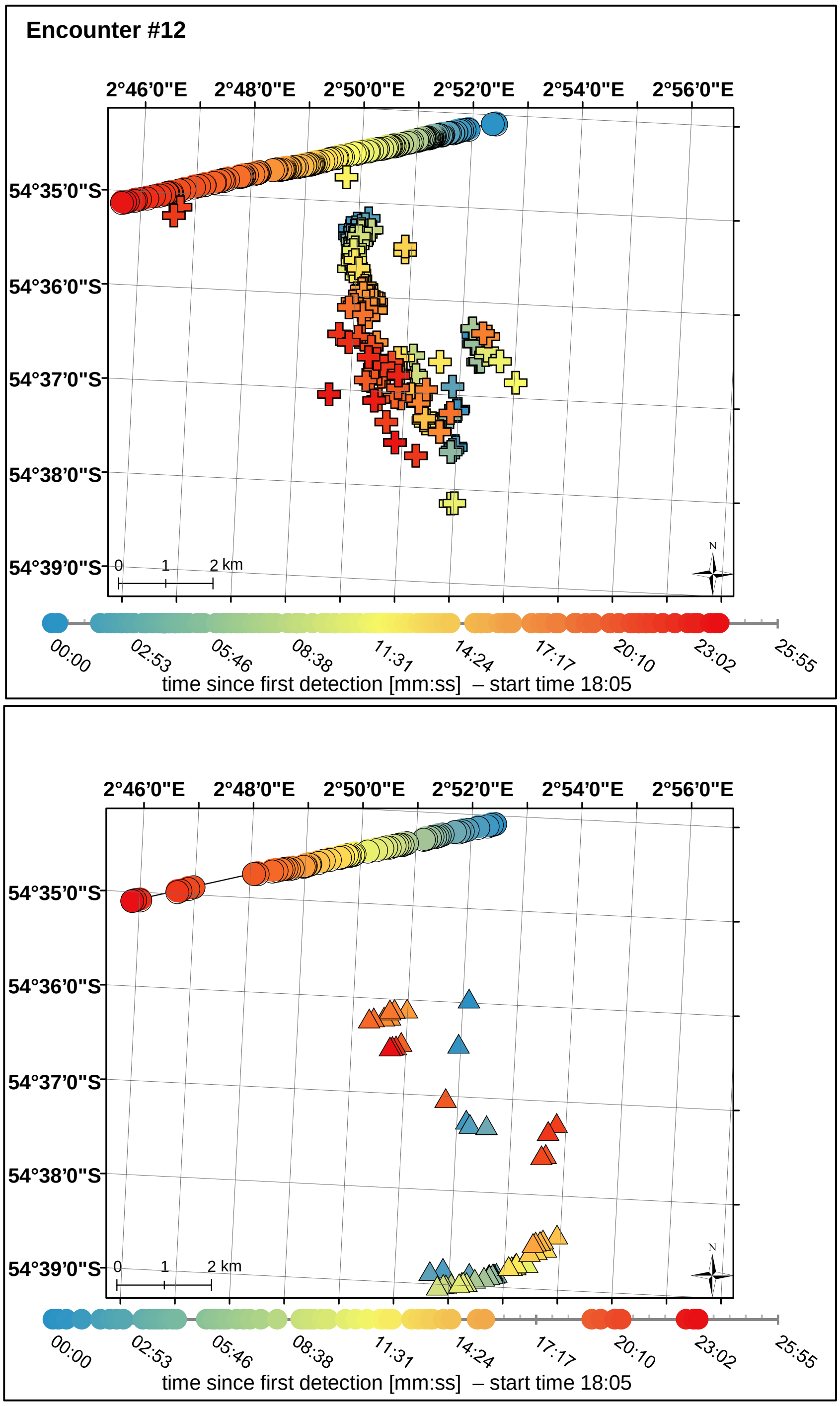


Fig. 65: Geo-referenced maps of encounter #12 based on thermal recordings (top; 164 events) and based on visual recordings (bottom; 58 events).

During this encounter, several pods were detected concurrently. The pod followed in the thermal video which was swimming perpendicularly to *Polarstern*'s path was not continuously followed by the visual observers and the movement pattern was not noticeable in their recordings. The pod observed by the MMOs in a distance of >9000 m appeared to move in the opposite direction of *PS*'s path. This movement could not be detected in the thermal stream and the maximum distance recorded was about 7700 m.

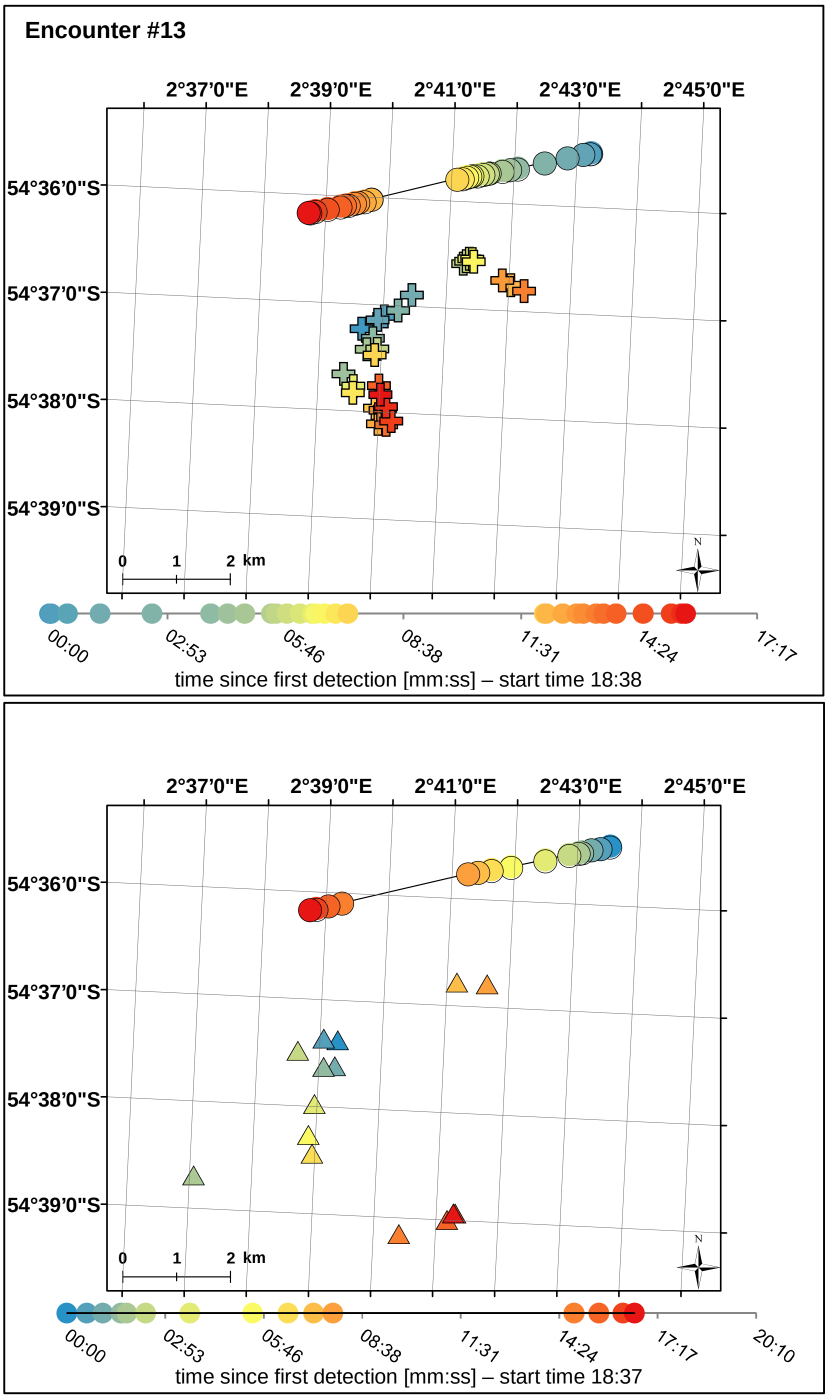


Fig. 66: Geo-referenced maps of encounter #13 based on thermal recordings (top; 29 events) and based on visual recordings (bottom; 15 events).

There were two pods detected during this encounter in the thermal stream and visually. The pod that was detected first was recorded to move obliquely away from *Polarstern*'s path, while the visual observers recorded the pod swimming straight away. The blows detected by the MMOs were more dispersed and the distances of the whales was estimated higher than in the thermal stream.

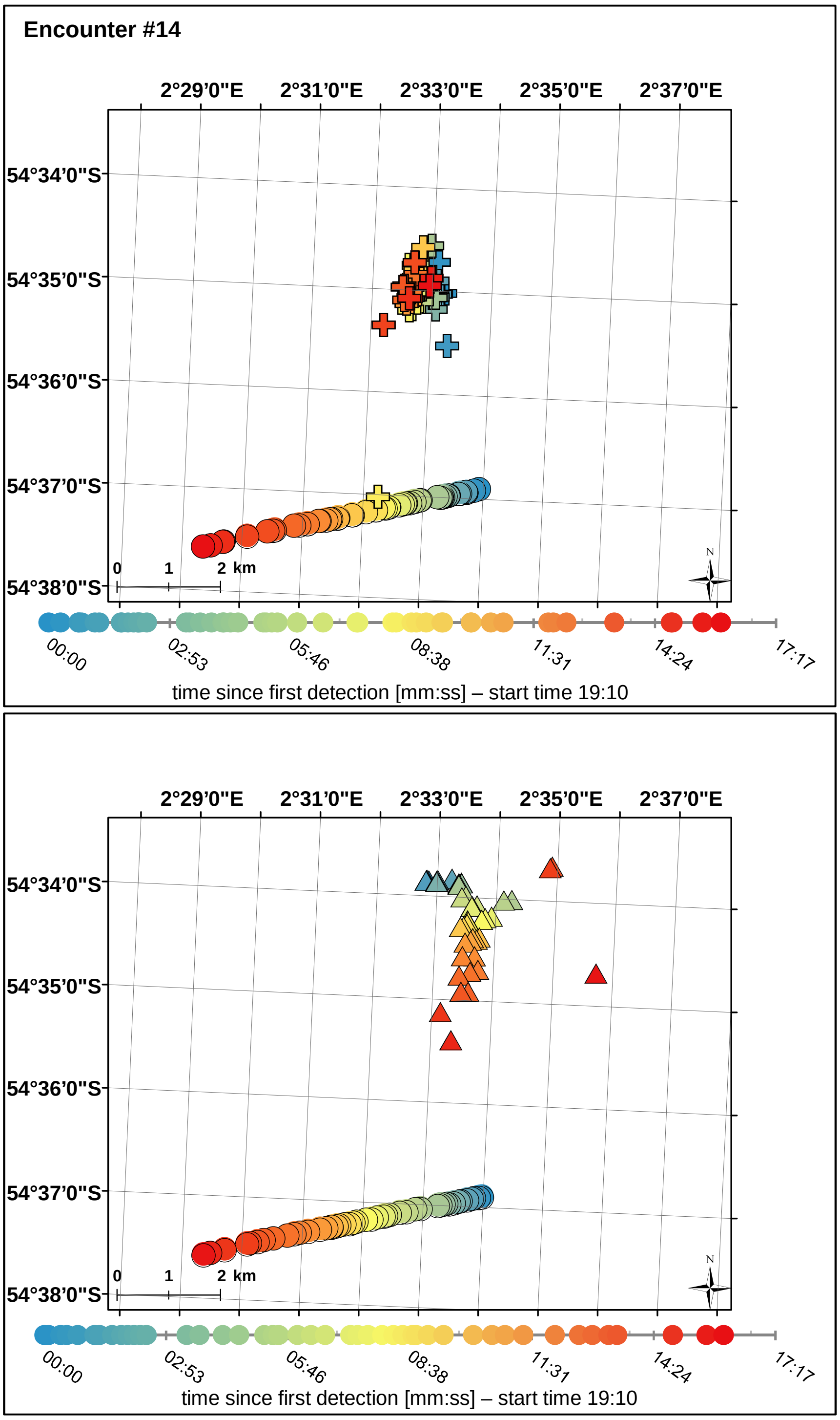


Fig. 67: Geo-referenced maps of encounter #14 based on thermal recordings (top; 51 events) and based on visual recordings (bottom; 45 events).

The focal pod was stationary in the thermal stream, while the visual recordings showed the pod swimming in a semicircle while moving towards the same direction as *Polarstern*.

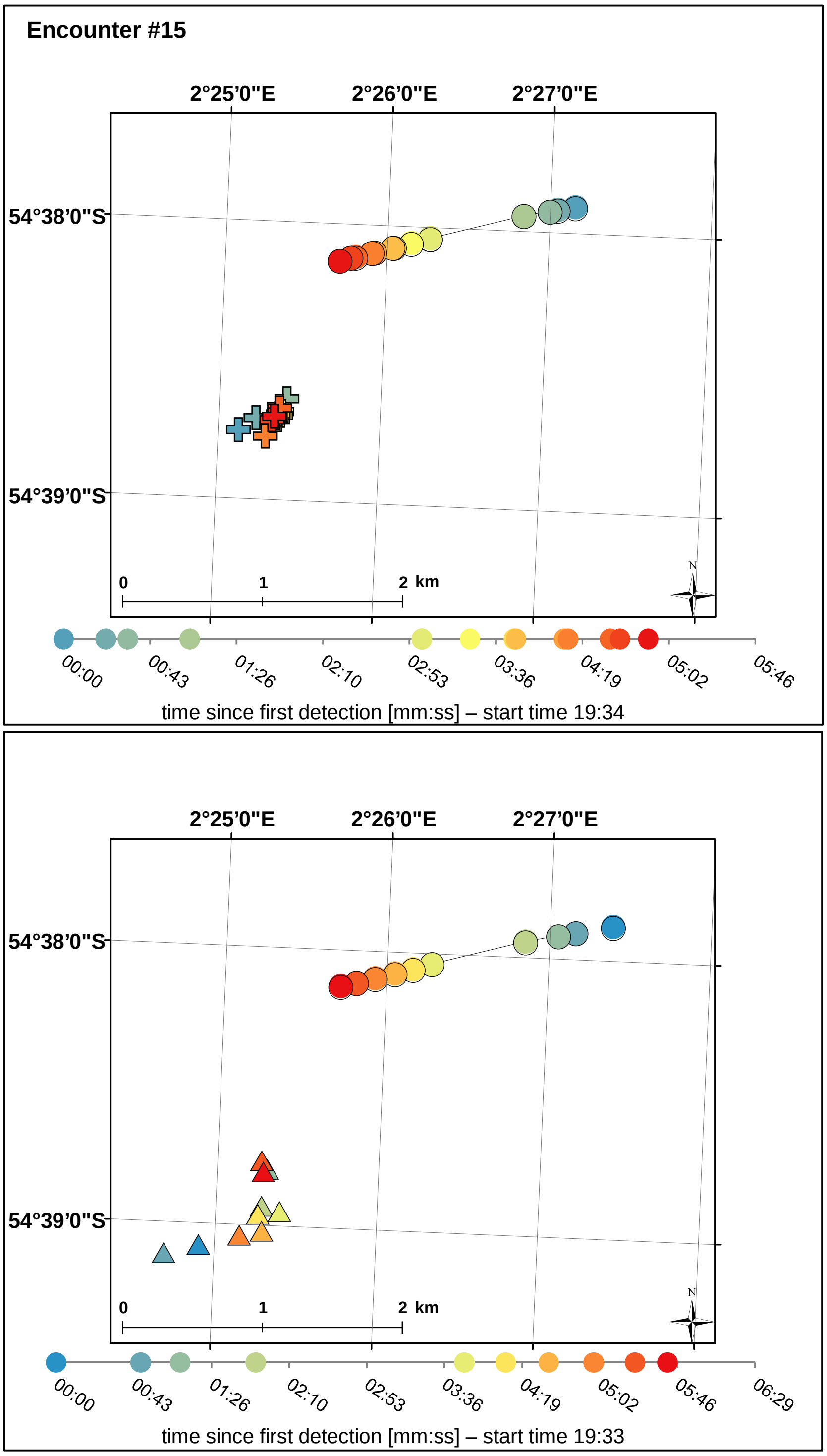


Fig. 68: Geo-referenced maps of encounter #15 based on thermal recordings (top; 14 events) and based on visual recordings (bottom; 10 events).
The events recorded in the thermal stream are less dispersed and in a closer distance to *Polarstern* than those recorded visually. In the thermal images the pod appeared rather stationary, while no clear orientation is recognizable from the visual recordings.

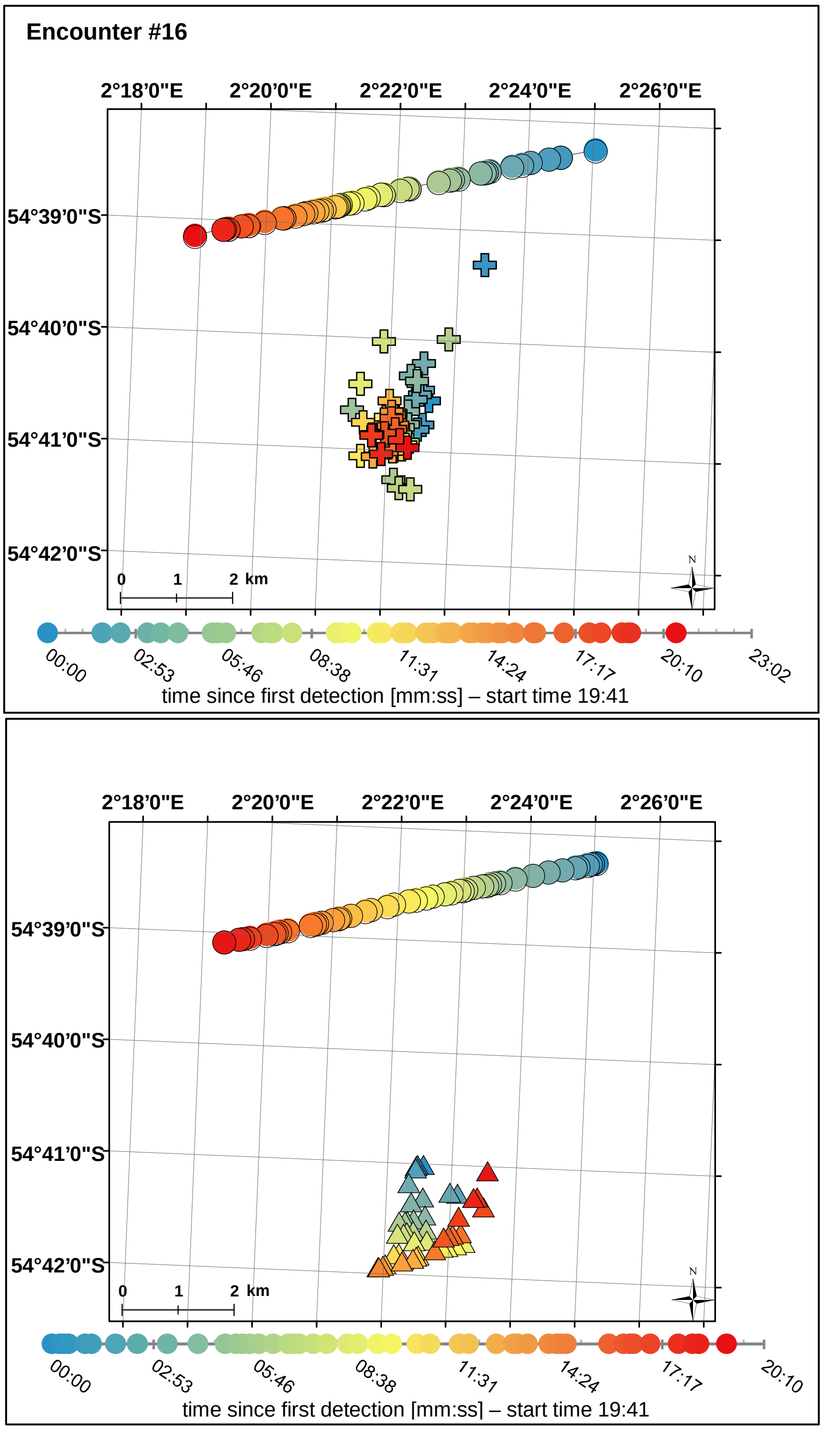


Fig. 69: Geo-referenced maps of encounter #16 based on thermal recordings (top; 50 events) and based on visual recordings (bottom; 46 events).

In the thermal stream, the pod appeared virtually stationary. According to the records of the visual observers, the pod was swimming in a semicircle towards the opposite direction than *Polarstern.* In general, the pod was estimated at a greater distance visually (>6200 m) than in the thermal images (2330-5350 m).

5. Discussion

5.1 Behavioural response of fin and humpback whales to *RV Polarstern*

Behavioural responses to *Polarstern* were observed in five of the 17 focal pods tracked during 6 hours in the Southern Atlantic in December, 2012. These pods changed their traveling direction as *Polarstern* approached them and turned away perpendicularly or to the opposite direction of the ship’s heading.

The behavioural responses of the five pods can be explained by the sound profile of *Polarstern* (Fig. 12, 13) which is in line with the phenomenon of acoustical shadowing. These pods were detected ahead of *Polarstern*’s path. Therefore, they received relatively low sound pressure levels because noise generated by the propellers was reflected by the ship’s stern. However, the shadowing effect is reduced with increasing angles resulting in increasing sound pressure levels. At angles greater than 45-50°, the received levels are loudest because the acoustical shadowing effect is repealed. When *Polarstern* closed in on the pods in #4, #5, and #7.2, they first kept traveling in a similar direction as *PS*. This enabled them to stay ahead of *Polarstern* at angles <45° where the received levels were relatively low. During the approach, the angles increased as the distance between *PS* and the pods became smaller due to *PS*’s higher speed. Since the received noise level increased from 95 dB at 0° to >120 dB at 45-50°, the whales avoided the highest received levels by swimming parallel to *Polarstern*’s path as long as angles were lower than 45° and they were in the *PS*’s shadow zone. As the angle between *PS* and a pod became larger than 45°, the whales could not avoid the highest sound levels by swimming parallel in front of *Polarstern*’s path any longer. Then, in order to reduce the sound intensity they were exposed to, it became more efficient to increase the distance to the sound source, i. e. *Polarstern*, due to transmission loss causing sound intensity to decrease as the square of range (Au & Hastings, 2008). A fast increase in the distance is achieved by turning away perpendicularly which is consistent with the behaviour shown by the pods of #4, #5, and #7.2.

Even though the pods of the encounters #2 and #7.1 did not travel parallel to *Polarstern*’s path, they showed the same behavioural reaction when the angle to the ship and the received level increased. The pod of #2 changed its direction even twice. First it turned away perpendicularly to *PS*’s path when the distance to *PS* was about 880 m at an angle of 22°. When the along-track-distance between *PS* and the pod was at its minimum, it turned again to the opposite direction of the ship’s heading. Similar, the focal pod of #7.1 also turned to the opposite direction when the along-track-distance was smallest after moving perpendicularly to *PS*’s path.

Even though the received levels remained rather constant at angles between 45° and 150°, the peak received level was reached at an along-track-distance of about 0 m, as the sound field measurement of *Polarstern* showed (Fig. 12). This peak is consistent with the shift in orientation to the opposite direction of *PS* from the focal pods #2 and #7.1. Additionally, since the distance between *PS* and the focal pods was at a minimum (ca. 500-600 m) when the animals changed their orientation, this change in direction might not only have been caused by increasing noise exposure due to increasing angles and, consequently, the vanishing of the effect of acoustical shadowing. Instead, it may have been the result of increasing sound intensity due to declining distance to the sound source. Again, the change in orientation increased the distance to the ship as fast as possible resulting in lower noise levels that the whales were exposed to.

However, it is difficult to say at which particular point during the encounter the whales were changing their direction. The events cannot be assigned to individual whales and their underwater behaviour cannot be observed. Hence, the angles between ship and whale at the time of the direction change range widely from 22-71°. The great variability of the data available for each pod can impede the unambiguous assessment of a pod’s behaviour.

The modelling largely matched these results inasmuch as showing that the movement of the pods that changed their travel direction differed from their models. For #4 and #7.2, the models showed that based on the first half of the detected events, the animals would have kept swimming virtually parallel to *Polarstern*’s path instead of changing their direction. The encounters #5 and #7.1 are difficult to compare to their models because of the low number of events after the whales apparently changed their direction. However, assuming that the whales maintained their new direction after the last detection, their paths differ from the modelled events that do not reflect the shift in orientation. Even though some of the modelled paths of #5 reach the last detections of the pod, the modelled paths maintain the same direction as the detected events that they are based on. In contrast, the events recorded in the end of the encounter suggest a change in the pod’s swimming direction.

The modelled events of encounter #2 are highly variable and cover a large area including all events detected during this encounter without a clear directionality. On the one hand, it seems like the whales shortened the distance covered between two surfacings after changing their travelling direction for the first time. On the other hand, this variability might partially be caused by the variation of the events that the modelling is based on. For example, the distance between the events 21 and 22 of this encounter is ~1400 m. So it seems likely that not all of the events in this encounter belong to a single pod but were impossible to distinguish. Therefore, the model of encounter #2 is probably not only based on events of the focal pod. The large variation makes it meaningless to compare the model with the actual events.

The focal pod of encounter #13 was not included in the number of pods showing a behavioural response to *Polarstern*. According to the comments made by the MMOs the events belonged to two different pods, while the recordings of the thermal images suggest a single pod displaying a behavioural response to *PS*. It is impossible to determine the membership of the animals retrospectively as it cannot be ruled out that indeed a second pod was tracked in the end of the encounter. However, it might as well be the same pod that dived for several minutes and was then detected again by the visual observers. The model of this encounter does not provide clarification. If there were two pods instead of one, then the mismatch between the modelled events and the detected events merely reflects the presence of another pod and not a behavioural response. In favour of doubt, the behaviour of the pod(s) in this encounter was classified as “no response / undefined behaviour”.

Pods that were rather stationary than traveling (#10, #11, #14, #15, #16) were most likely either foraging or resting, for instance, as indicated by a comment made by the MMOs during encounter #11 (“3 animals, just logging”). These encounters are in consistency with their respective models which reflect the stationary behaviour, even though the models of #10 and #15 appear less stationary than the events actually detected. None of these pods showed a behavioural response. With the exception of #15, the closest distance in which a pod was detected was 3390 m which is relatively far away compared to the distances to the pods showing a behavioural response. This means that they were exposed to considerably lower sound pressure levels. The observation of the pod of encounter #15 stopped at an angle of 53°. Hence, a possible change in the behaviour of this pod to *Polarstern* at a later point was not observed. The other pods were detected at greater angles (>45°) at which the intensity of the noise exposure was highest and did not change substantially anymore. Hence, the behaviour of all of these pods could be analysed only temporarily.

The pods of encounter #1, #8 and #12 were traveling without reacting to *Polarstern.* During encounter 1#, a pod of at least eight fin whales was tracked. Even though the pod seemed to turn away from PS’s path, it is difficult to assess its behaviour because the whales were dispersed over a comparatively large area and due to the high number of overlapping blows. However, in the end, the whales seemed to turn back again and move to the same direction as *PS* which was not observed in any of the pods showing a behavioural response. The pod of #8 was the only one detected within 1000 m of the ship without displaying a behavioural response. However, it was only followed at angles ranging from 30-96° ahead and to the side. Since the observation stopped at this point, a possible behavioural response occurring later could not be observed. During the encounter, they were traveling in a straight line with a slight turn to the left in the end of the encounter. The model of #8 reflects the constant direction. Pod #12 was detected at a distance of approx. 3000 m and, additionally the minimum distance during this encounter was rather large compared to most of the pods displaying a behavioural reaction. Even though the whales appear to turn away from *Polarstern* in the beginning, they maintain a virtually constant direction during the encounter which matches the model.

The focal pods of the encounters #3, #6, and #9 were detected at angles of >80° making it impossible to assess the behaviour and possible behavioural changes that may have occurred earlier. The minimum distances during these encounters were rather large with more than 2500 m. Additionally these encounters are comparatively short and comprise only a few events because the pods could only be followed in a small angular range due to the detection at a large angle and the camera's usable observation angle. Besides, encounter #6 could only be analysed partially due to lack of corresponding thermal video recordings. The low number of events also made it impossible to generate models for these encounters.

The short duration and low number of events of some encounters, the detection at great angles, and the fact that not all focal pods were tracked until they were out of the camera's usable observation angle are the result of the opportunistic nature of the data on which this analysis is based. These limitations entail restrictions on the validity of some of the ship-whale encounters because only a temporary part of the behaviour could be analysed and some encounters were too short to define the behaviour at all.

Three out of four pods that were detected within 1000 m from the ship displayed behavioural responses during the encounter, and two out of four pods tracked within 1000-2000 m, while none of the nine pods observed in distances between 2000-4000 m showed a response to *Polarstern*. This distribution suggests that proximity is an important factor influencing the behavioural responses of whales. Reactions to noise from marine mammals often increase with increasing signal intensity (NRC, 2005). Since sound intensity declines with increasing distance to the sound source due to transmission loss, pods at greater distances to *Polarstern* were exposed to lower received levels that did not trigger a response. These results suggest that the whales displaying a behavioural response tried to avoid high received levels, first by swimming in front of *Polarstern* in her shadow zone, then by changing their travel direction and increasing the distance to *PS*.

Human disturbance of wildlife is commonly viewed as issue of concern in biodiversity conservation (Gill, 2007), and behavioural responses are frequently used to measure and evaluate its effect on individuals and populations (Gill et al., 2001). However, when investigating an animal's susceptibility to human interference, the intensity of responsiveness is not necessarily appropriate as behavioural index of fitness consequences. Animals responding most might be the ones in good condition while those not showing a reaction might be those with most to lose from changing their behaviour (Gill et al., 2001). This could be another explanation for that none of the stationary pods of fin and humpback whales (#10, #11, #14, #15, and #16) that might have been foraging or feeding displayed a behavioural reaction to *Polarstern*. Gunther (1949) also reported fin whales to usually move away slightly as a ship approached but less responsive when feeding. Similarly, a lower responsiveness to ships while feeding has been suggested for sei whales (Lockyer, 1981); and surface-feeding blue whales were reported less reactive to simulations of mid-frequency military sonar than non-feeding and deep-feeding animals (Goldbogen et al., 2013). According to the authors, the higher energetic efficiency of surface-feeding compared to deep feeding (Goldbogen et al., 2011) may have increased the whales' motivation to continue surface feeding.

Even though animals might assign different priorities to different activities (Gill et al., 2001), wild animals rarely engage in activities that are not biologically significant (NRC, 2005). For instance, resting is also fundamentally important to the health of many species (Constantine et al., 2004), and has been documented to decrease due to human disturbance (e.g. bottlenose dolphins *Tursiops sp.*, Lusseau, 2003). A decline in resting behaviour probably leads to a reduction of energy reserves, which in turn could reduce the foraging efficiency, vigilance levels, and the level of parental care (Constantine et al., 2004).

Behavioural responses occurred in both fin and humpback whales implying that all baleen whales are susceptible to vessel noise. This result is in consistency with a range of literature reporting effects of noise in various baleen whale species and other cetaceans. Richardson et al. (1990) reported bowhead whales avoiding playbacks of noise from drillships and estimated the radius of responsiveness between 3 and11 km. Humpback whales showed behavioural responses to vessels operating within 4000 m (Baker & Herman, 1989); and Common minke whales were even displaced by increased vessel noise from an open bay (Anderwald et al., 2013). Au & Perryman (1982) documented avoidance behaviour of three dolphin species (spinner dolphins *Stenella longirostris* pantropical spotted dolphin *Stenella attenuate*, striped dolphin *Stenella coeruleoalba*) to an approaching ship in distances of at least 6 nm (11.1 km). Model estimations showed a zone of behavioural disturbance of beluga whales *Delphinapterus* *leucas* within almost 80 km around an icebreaker, only slightly smaller than the zone of audibility (Erbe & Farmer, 2000).

It is unknown how cetaceans interpret anthropogenic noise (Goldbogen et al., 2013). The similarity between stereotyped killer whale calls and military sonar signals has lead researchers to the predator evasion hypothesis (Zimmer & Tyack, 2007). Mammal-eating killer whales are the only known natural predators of many cetacean species including baleen whales (e. g. Ford & Reeves, 2008; Notarbartolo-di-Sciara, 1987), and the evolution of behaviour is strongly driven by effects of predation (Deecke et al., 2002).

Ship noise differs from military sonar signals in many characteristics and confusion with killer whale calls seems unlikely. Besides, fin and humpback whales showed generally the same behavioural responses to *Polarstern.* Although the swimming speed of individual animals and possible differences in speed between the species could not be determined, both fin and humpback whales responded by turning away from *PS*'s path and increasing the distance. In contrast, these species typically follow different strategies when confronted with killer whales (Ford & Reeves, 2008). Furthermore, behavioural changes were mainly seen in focal pods that were relatively close to *Polarstern*. Considering this in addition to the consistency between the behavioural response shown by the whales and the sound profile of *Polarstern*, it seems most likely that here the sound intensity itself triggered a response of the whales.

Nevertheless, derived from the predator evasion hypothesis, blue whales traveling away from a sound source emitting simulated sonar signals with an increased swimming speed were suggested to display a “generalized avoidance response of a perceived threat” (Goldbogen et al., 2013). Walther (1969) was the first to assume that disturbance stimuli can evoke behavioural responses analogous to predation risk (for a review see Frid & Dill, 2002), and Dill (1974*a, b*) documented that animals have evolved antipredator responses to generalized threatening stimuli such as loud noises and rapidly approaching objects. This has also been suggested for the behaviour of killer whales to boats (Williams & Ashe, 2007; Williams et al., 2002), and may have contributed to the fin and humpback whales' behaviour.

The received level of the recorder on the zodiac of the ship noise generated by *Polarstern* ranged from 95 dB right ahead of her path to a maximum of 124 dB. With a length of ca. 118 m, *Polarstern* has a length comparable to most merchant vessels (84-122 m; Tab. 2). Merchant vessels at a similar speed as *Polarstern* during the sound field measurement have source levels of 137-165 dB depending on the frequency. With increasing size and increasing speed, source levels of ships ascend up to 189 dB in supertankers (244-366 m) at 18-22 kn. Over all vessel types, the highest source levels were calculated at 10-50 Hz (161-189 dB) while source levels at

100 and 300 Hz were considerably smaller (137-175 dB). In the view of these source levels, it seems most likely that ships larger and faster than *Polarstern* also produce higher sound levels and insonify a greater area than her posing a greater source of disturbance for baleen whales and other marine life. Considering this in addition to the distance in which behavioural responses to *Polarstern* were detected, the global scale at which whales and other cetaceans are potentially disrupted by vessel noise seems significant. Here, behavioural responses suggest that whales were avoiding high sound levels and were detected in pods at minimum distances of up to ~1500 m. The radius of audibility is probably much greater as animals might not respond to sounds that are just audible, but only react to a sound that is a certain level louder (Erbe, 2002).

A human-caused increase in low-frequency ambient noise must be considered a potential stressor for all baleen whales (NRC, 2005). Depleted populations and those exposed to cumulative impacts of multiple stressors might be at greater risk (NRC, 2005). Stress can have adverse effects on survival and/or reproduction of animals (Curry, 1999), and is thought to be involved in the lack of recovery of dolphin populations (Gerrodette & Forcada, 2005). Rolland et al. (2012) showed a correlation between a reduction of underwater noise of 6 dB and a decrease in baseline levels of stress-related hormone metabolites (glucocorticoids) in North Atlantic right whales. This study provides first evidence that low-frequency vessel noise may be linked to chronic stress in baleen whales.

However, up to this day, impact assessment of human disturbance has often been based on short-term behavioural responses (Gill et al., 2001) despite the fact that the biological significance of behavioural changes is still unknown due to challenges in studying free-living large whales (NRC, 2005). Therefore, it is important to link the effects of these changes to long-term individual vital rates, and cumulative effects of disturbance and synergistic effects with other stressors have to be taken into consideration (NRC, 2005). Nevertheless, seemingly small changes in behaviour can have strong demographic effects (Gerrodette & Gilmartin, 1990). Castellote et al., (2012) have suggested that anthropogenic noise can permanently increase the energetic cost critical of life functions as communication; and Goldbogen et al. (2013) showed disruption of deep-feeding behaviour of blue whales which results in reduced foraging efficiency and decreases the energetic intake. Impacts of anthropogenic noise on blue whales and their habitat have been hypothesized to limit the species' recovery (Sears & Perrin, 2009).

There are only a few studies estimating energetic costs of human disturbance in cetaceans. Williams et al. (2006) documented decreased feeding behaviour of Northern Resident killer whales in the presence of boats in British Columbia, Canada, over a period of seven years. The lost feeding opportunities could have resulted in a substantial estimated decrease in the energetic intake of 18%. Feeding disruptions of Common minke whales by boats (Christiansen et al., 2013*a*) and an increased energy expenditure during the feeding season in Southwest Iceland were estimated to lead to a possible decrease in energy intake of ca. 63.5% (Christiansen et al., 2014). However, after estimating the cumulative exposure of individual minke whales to human disturbance, potential long-term effects were found to be negligible (Christiansen et al., 2015).

Since the susceptibility to human disturbance may be species-specific (Constantine, 2001), and the exposure of marine mammal populations to disturbance may differ in duration and frequency, these results are not necessarily transferable to other populations and species. In the Mediterranean Sea, for example, fin whales are assumed to be among the species most sensitive to shipping and seismic noise (Castellote et al., 2012). Intensive whaling near the Strait of Gibraltar in the recent past (Clapham et al., 2008) and high genetic isolation (Palsbøll et al., 2004; Bérubé et al., 1998) probably aggravate their status (Castellote et al., 2012). Therefore, all factors influencing the current status of any population should be taken into consideration in conservation management.

There are several approaches to protect marine species from ship noise. First steps would be the development of an objective standard for measuring radiated vessel sound and the implementation of quieting technologies on vessels (IMO, 2014). The largest potential lies in the initial design of the ship, including hull design, onboard machinery and – most important – the propeller design and selection to reduce cavitation. Even though there are also suggestions for existing ships (e.g. installation of new propellers, maintenance of a smooth underwater hull surface; IMO, 2014), retrofitting would be a costly and, thus, unlikely undertaking, and the implementation of large-scale technological changes will take several decades (Hatch et al., 2008). However, there is a substantial difference between the hydroacoustic noise levels generated by ships (Renilson et al., 2012; Leaper & Renilson, 2012). Therefore, the implementation of quieting technologies on only the loudest part of the world’s commercial fleet could have a significant effect on the ambient noise level (IMO, 2013). The introduction of a speed limit for certain ships (IMO, 2014) seems suitable for a rather quick and simple noise reduction. Generally, as the commercial shipping fleet is registered in a wide range of countries and most shipping noise is produced in international waters (MMC, 2007) efficient regulation of shipping noise takes a considerable international cooperation. The IMO has set up a range of guidelines for reducing ship noise (IMO, 2014). However, they are not legally binding.

From a management perspective, rerouting and consolidation of shipping lanes based on passive acoustic monitoring data may help to relief areas with a high density of marine mammals

(Dransfield et al., 2014; Hatch et al., 2008). The establishment of Marine Protected Areas (MPAs) with exclusion zones and additional buffer zones has also been suggested (Wright et al., 2011; Hatch et al., 2008).

Thermal imaging has proven to be applicable for behavioural analysis of baleen whales – at least to follow the movement of whales - even if the retrospective analysis of the thermal video stream is a time-consuming process. At first detection, the travel direction of a whale cannot be identified in the thermal images but if an animal or a pod is tracked over time, it is cleared up. However, there are limitations that have turned out to seriously complicate the analysis. Most challenging is the inability to assign events to individual whales. Parameters like swimming speed, respiratory rate, dive duration etc. that are typically used to assess behavioural disruption of cetaceans, cannot be determined on an individual-level using this detection method unless only a single animal is tracked. Nevertheless, a general behavioural analysis of a pod is still feasible as shown in this thesis. For the most part, the modelling has turned out applicable as support for this analysis; however, in order to get meaningful results it is important to have data with a quality and quantity sufficient for the modelling to be practicable.

A widespread use of an infrared-based camera system on ships could not only be used for a substantial increase of data on behavioural reactions of cetaceans to anthropogenic noise (ship noise, seismic surveys, sonar) but it could also be a useful tool in collecting large amounts of data on the distribution and abundance of species and for the identification of important marine mammal habitat. This information could be powerful groundwork for future conservation management.

5.2 Comparison of thermal imaging based and visual whale detection

The comparison between the thermal imaging based and visual detection indicates that thermal imaging is more efficient for whale detection, more precise in determining the distance of a whale and is better for behavioural analysis than visual observers using binoculars on a moving platform during high sea states. During 6 h of observation, 1.5 times more events were detected by human screening of the infrared recordings than by the visual observers with up to 2.6 times more events during one encounter. The number of animals is also easier to determine in the thermal images as the number of animals was often underestimated by the MMOs.

Furthermore, there is a greater variation within the distance estimations of events by the visual observers. For instance, during the encounters #9 and #14 only one pod was tracked both by the visual observers and in their thermal recordings. However, some events were estimated at considerably larger distances by the MMOs than the rest of their records and the events detected in the thermal recordings. In #9, most of the events were detected in a distance of approx. 3730 m while some events were detected at ~6210 m. The events detected in the corresponding thermal video and the comments of the MMOs indicate that these events belong to the same pod. Similar to this, some events of encounter #14 were estimated at a distance >9000 m by the visual observers while they estimated the rest of the pod at ~6200 m distance. Additionally, the distances of whales estimated by the MMOs and estimated based on the thermal images were considerably different. In the range between 1000 and 6000 m, the visual observers overestimated distances of whales significantly which is probably the result of the large error if the distance is estimated using binoculars. For distances smaller than 1000 m, it is easier to determine the distance to a whale both for the MMOs and in the thermal images. At greater distances, the error in distance estimation increases for both detection methods (Fig. 18) so that at distances greater than 6000 m there is no substantial difference between the detection methods anymore.

Considering that visual monitoring is the primary and usually sole method of animal detection for mitigation these findings are cause for concern. Even if animals are detected, the observers might not trigger a shutdown of the sound source due to the overestimation of the distance. In Australia, for instance, the exclusion zone is 3000 m around an airgun source (Weir & Dolman, 2007). However, events that were detected at an average distance of ~2550 m in the thermal recordings were estimated at ~3370 m by the visual observers. Thus, no shutdown would have been triggered for these animals even though they had entered the exclusion zone.

Species identification based on the thermal images is impossible requiring visual observers or an extension of the system by installing a second visual camera to take pictures usable for species ID (see Zitterbart, 2013). Here, the visual observers were able to identify the species in 13 of the 17 encounters with minimum distances ranging from 410-3600m. Not surprisingly, the minimum distances of the unidentified pods ranged from 2570 to 3860 m. For mitigation purposes, however, species identification is of minor relevance since the radius of the exclusion zone is typically the same for all baleen whale species (Dolman et al., 2009).

The ability to detect more events than visual observers and to determine a whale's position more precisely contribute to the ability to analyse the behaviour of whales based on the thermal images. Based on the visual recordings of the MMOs, only the pod of #2 turned away from *Polarstern*'s path. The behavioural responses of the other three pods (#4, #5, #7.1, #7.2) was not recognized as such as the pods did not show a clear direction in the maps based on the visual data. This is probably caused by the specification of the distance to the whales in steps of

0.25 reticules, the error in distance estimation and its variation with distance which does not allow to detect small differences in distances and to follow the continuous track a pod of whales. This explains also the seemingly movement of the stationary pods of #10, #14 and #16. As the distance between *Polarstern* and the pods became smaller during the encounters, the visual observers still estimated the same distance as it was given in steps of 0.25 reticules. Therefore, the pod seemed to move as *Polarstern* was approaching and moving away even though it was actually stationary.

Besides, it is possible to track several pods concurrently in the IR which is impossible to do for visual observers. For example, the MMOs thought to follow only one focal pod during encounter #7; however, two pods were identified and tracked in the thermal images. Also during encounter #2 and #12, more pods were detected in the IR recordings, while the MMOs had to switch between pods during #12 (comment “switched to fin whale”). So it seems easier to identify and distinguish pods in the thermal recordings than visually. In encounter #6, the large difference of about 40° between the visual detections and thermal imaging based detection indicates that different pods were tracked during this encounter.

Generally, the effectiveness of optical detection systems is affected by environmental conditions. Here, weather conditions do not seem to have played a critical role for thermal imaging based whale detection. Even though wind speeds were constantly ≥13 kn (≥4 Bf) and sea states were rather high, it was still possible to detect whale blows reliably, and high relative humidity of up to 91 % that may lead to an attenuation of signals in thermal images (Baldacci et al., 2005) did not seem to be obstructive. For comparison, Baldacci et al. (2005) tested an infrared binocular that was reported to be strongly affected by weather conditions and ineffective with sea state greater than 2-3. Good visibility (> 10000 m) and low air and water temperatures (between -0.6 and 0.9°C and between -0.5 and -0.1, respectively) remained fairly constant throughout the observation period, and there was no precipitation that would have impeded whale detection in the thermal images as well as the visual detection.

Here, visual observers were generally unable to assess the behaviour of a pod of whales as neither behavioural responses nor stationary behaviour was recognized reliably. Difficulties for observers to study ship-avoidance behaviour from a “surface platform” have been noted before (Au & Perryman, 1982). This is mainly caused by the large error that MMOs make in the distance estimation. Considering these results, there is currently no efficient and reliable mitigation measure ensuring that marine mammals are protected from noise exposure during seismic surveys. Infrared camera systems with automatic whale detection (Zitterbart, 2013) represent a suitable alternative; however, they are usually not mandatory and not widespread.

6. Conclusions and outlook

Global vessel traffic is likely to further increase in the future. World shipping activity is in the process of doubling from 2002 by about 2030 (Corbett & Windebrake, 2008; National Oceanic and Atmospheric Administration (NOAA), 2004). The decline of Arctic sea ice that has been observed over the past decades opens the opportunity to establish new trade passages (Jakobson, 2010; ACIA, 2004). Additionally, tourism is regarded one of the few economic opportunities in the Arctic and Antarctica (Hall & Saarinen, 2010). In Antarctica, it has developed rapidly over the last two decades, including ship-based tourism, and more and larger cruise liners are expected to enter Antarctic waters (Lamers et al., 2008). These developments also mean increased vessel traffic in ecosystems that have been comparatively unaffected by (commercial) shipping up to now and are important habitats for a range of marine mammal species. Even though predictions of rising sound levels generated by the world's shipping fleet based on increases in speed and lengths are not without controversy (e.g. Heitmeyer et al., 2003), ocean noise is directly linked to increasing industrialization (NOAA, 2004; NRC, 2003).

However, there are ways to lessen the impact of various sources of anthropogenic noise on marine animals. A reduction of noise from seismic surveys could be achieved by developing more efficient airgun arrays and avoiding repetitious seismic surveys in the same area (MMC, 2007). Marine vibroseis (MV) systems have also been proposed for mitigation, as a smaller amount of sound is used over a longer period of time compared to seismic surveys. However, their use has been largely restricted to situations where airgun arrays are not applicable, such as on sea ice (LGL & MAI, 2011). Furthermore, a new technology exploiting weak seismic waves generated by ocean waves can be used to monitor the oceans' subsurface in real-time (Ridder et al., 2015). In contrast to conventional seismic surveys, this so-called *ambient seismic field noise-correlation tomography* works passively without airgun blasts that could harm marine animals. For activities like pile-driving, underwater air bubble curtains have been developed that can reduce noise by inhibiting sound transmission. Studies have shown noise reduction and decreased avoidance behaviour of marine mammals after installation of bubble curtains at construction sites (Lucke et al., 2011; Würsig et al., 2000). While most European countries require the use of bubble curtains during piling activities (Erbe, 2012), it remains to be seen in how far conventional seismic surveys will be improved (in terms of sound pressure levels) or even replaced by new technologies in the future.

For the conservation of species, human disturbance of wildlife is relevant only if it has adverse impacts on survival or fecundity and, hence, causes a population to decline (Gill et al., 2001). However, fitness costs of changes in behaviour need to be quantified before they can be used for estimations of the consequences of disturbance on the population-level (NRC, 2005; Gill et al., 2001). Currently, the amount of data is not sufficient to infer from short-term changes in behaviour to shifts in demographic parameters of a population which highlights the need for research to explore this connection. However, if anthropogenic noise further increases in the future, the scale at which disturbance might occur expands and so does the potential for negative biological significant impacts on marine mammals. Further research will be necessary to be able to predict long-term effects on marine mammal populations from behavioural and physiological effects of anthropogenic noise on individual marine mammals.

In order to better understand the potential impact on local populations, the establishment of “noise budgets” for different areas of the ocean has been suggested (NRC, 2003). These budgets represent the total amount of relative contributions made by identified sound sources to a total noise field. The NRC (2003) recommended to define sound contributions of different vessel types and to specify temporal and spatial variation of noise production and sound fields. Knowledge about the main sound sources in an area together with knowledge on the marine mammal species inhabiting this area could then be used to decide on the most effective mitigation measures to protect marine mammals, while special attention should be paid to areas with high levels of vessel traffic, e.g. the Mediterranean Sea, the North Sea, the U.S. East coast (Halpern et al., 2008), and to vulnerable and endangered populations.

References

ACIA: Impacts of a Warming Arctic: Arctic Climate Impact Assessment (2004) Cambridge University Press, 140 pp.

Albert, H.P., Dobinsky, H. Hoffmann, K., Linkw, B., Nitzschmann, U., Bole, C., Lederer, K., Pruin, B., Krappinger, O., Schwarz, J. (1983) Das deutsche Polarforschungs- und Versorgungsschiff "Polarstern". Sonderdruck aus HANSA 6/1983 für Alfred-Wegener-Institut für Polarforschung, Bremerhaven. Retrieved from http://epic.awi.de/20619/ on December 3, 2014.

Allen, J.K., Peterson, M.L., Sharrad, G.V., Wright, D.L., Todd, S.K. (2012) Radiated noise from commercial ships in the Gulf of Maine: Implications for whale/vessel collisions. J. Acoust. Soc. Am., 132(3): EL229-EL235.

Alling, A.K., Payne, R. (1991) Song of the Indian Ocean blue whale in *Balaenoptera musculus*. In: Leatherwood, S., Donovan, G.P. (eds.) Cetaceans and Cetacean Research in the Indian Ocean Sanctuary. United Nations Environment Programme, Marine Mammal Technical Report, 3: 33-65.

Alling, A.E., Dorsey, E.M., Gordon, J.C. (1991) Blue whale (*Balaenoptera musculus*) off the Northeast Coast of Sri Lanka: distribution, feeding, and individual identification. In: Leaderwood, S., Donovan, G.P. (eds.) Cetaceans and Cetacean Research in the Indian Ocean Sanctuary (UNEP Marine Mammal Technical Report, 3: 247-258.

Andersen, S. (1970) Auditory Sensitivity of the Harbor porpoise (*Phocoena phocoena*). Invest. Cetacean, 2: 255-259.

Anderwald, P., Brandecker, A., Coleman, M., Collins, C., Denniston, H., Haberlin, M.D., O'Donovan, M., Pinfield, R., Visser, F., Walshe, L. (2013) Displacement responses of a mysticete, an odontocete, and a phocid seal to construction-related vessel traffic. Endang. Species Res., 21: 231-240.

Andrew, R.K., Howe, B.M., Mercer, J.A. (2002) Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. ARLO, 3: 65-70. Doi: 10.1121/1.1461915.

Archer, F.I., Morin, P.A., Hancock-Hanser, B.L., Robertson, K.M., Leslie, M.S., Bérubé, M., Panigada, A., Taylor, B.L. (2013) Mitogenomic Phylogenetics of Fin Whales (*Balaenoptera physalus spp.*): Genetic Evidence for Revision of Subspecies. Plos One, 8(5). Doi: 10.1371/journal.pone.0063396.

Au, W.W.L., Hastings, M.C. (2008) Principles of Marine Bioacoustics (Modern Acoustics and Signal Processing). Springer, New York, 680 pp.

Au, D., Perryman, W. (1982) Movement and speed of dolphin schools responding to an approaching ship. Fishery Bulletin, 80(2): 371–379.

Awbrey, F.T., Evans, W.E., Stewart, B.S. (1983) Behavioral responses of wild beluga whales (*Delphinapterus leucas*) to noise from oil drilling. J. Acoust. Soc. Am., 74 (Suppl. 1:54).

Baker, C.S., Herman, L.M (1989) Behavioural responses of summering humpback whales to vessel traffic: Experimental and opportunistic observations. Technical Report NPS-NR-TRS-89-01. United States Department of the Interior. National Park Service.

Baldacci, A., Carron, M., Portunato, N. (2005) Infrared detection of marine mammals. Technical report SR-443. NATO Undersea Research Centre.

Baraff, L., Weinrich, M.T. (1993) Separation of humpback whale mothers and calves on feeding ground in early autumn. Mar. Mam. Sci., 9(4): 431-434.

Bejder, L., Samuels, A., Whitehead, H., Gales, N., Mann, J., Connor, R., Heithaus, M., Watson-Capps, J., Flaherty, C., Krützen M. (2006) Decline in Relative Abundance of Bottlenose Dolphins exposed to long-term Disturbance. Conserv. Biol., 20(6): 1791-1798.

Bérubé, M., Aguilar, A., Dendanto, D., Larsen, F., Notarbartolo di Sciara, G., Sears, R., Sigurjónsson, J., Urban, R.J., Palsbøll, P.J. (1998) Population genetic structure of North Atlantic, Mediterranean Sea and Sea of Cortez fin whales, *Balaenoptera physalus* (Linnaeus, 1758): analysis of mitochondrial and nuclear loci. Mol. Ecol., 7: 585–599.

Blue, J.E., Gerstein, E.R. (2005) The acoustical causes of collisions between marine mammals and vessels. In: Medwin, H (edt.) Sounds in the Sea. From Ocean Acoustics to Acoustical Oceanography. Camebridge University Press, Cambridge, 643 pp.

Boebel, O. (2013) Reports on Polar and Marine Research. The Expedition of the Research Vessel "Polarstern" to the Antarctic in 2012/2013 (ANT-XXIX/2). hdl:10013/epic.42735.d00.

Bombosch, A. (2013) Modelling Habitat Suitability of Humpback and Antarctic Minke Whale Feeding Grounds in the Southern Ocean. PhD thesis.

Boyd, I.L. (2009) Antarctic marine mammals. In: Perrin W.F., Würsig B., Thewissen J.G.M. (eds.) Encyclopedia of marine mammals. Academic Press, New York, NY, 1352 pp.

Brodie, P.F. (1975) Cetacean energetics, an overview of intraspecific size variation. Ecology, 56: 152-161.

Brown, M.R., Corkeron, P.J., Hale, P.T., Schultz, K.W., Bryden, M.M. (1995) Evidence for a sex-segregated migration in humpback whales, *Megaptera novaeangliae*. Proc. R. Soc, 259:229-234.

Brown, B.E., Halliday, R.G. (1983) Fisheries resources of the Northwest Atlantic: some responses to extreme fishing perturbations. In: Por, E. (edt.) Proceedings of the Expert Consultation to Examine Changes in Abundance and Species Composition of Neritic Fish Resources. FAO Fisheries Reports, no. 291. In: Clapham, P., Young, S., Brownell, Jr., R. (1999) Baleen Whales: Conservation Issues and The Status Of The Most Endangered Populations. Mammal Rev., 20(1): 35-60.

Burns, J.J., Kelly, B.P., Aumiller, L.C., Frost, K.J., Hills, S. (1982) Studies of ringed seals in the Alaskan Beaufort Sea during winter: impacts of seismic exploration. Report from the Alaska Department of Fish and Game, Fairbanks, AK, for the Outer Continental Shelf Environmental Assessment Program, NOAA, 57 pp.

Byrant, P.J., Lafferty, C.M., Lafferty, S.K. (1984) Reoccupation of Laguna Guerrero Negro, Baja California, Mexico, by Gray Whales. In: Jones, M.L., Swartz, S.L., Leatherwood, S. (eds.) The Gray Whale *Eschrichtius robustus*. Academic Press, Inc., Orlando, Florida., 600 pp.

Castellote, M., Clark, C.W., Lammers, M.O. (2012) Acoustic and behavioural changes by fin whales (*Balaenoptera physalus*) in response to shipping and airgun noise. Biol. Cons., 147: 115-122.

Cato, D.H. (1976) Ambient sea noise in waters near Australia. J. Acoust. Soc. Am., 60:320–328.

Clapham, P.J. (2000) The humpback whale. Seasonal Feeding and Breeding in a Baleen Whale. In: Mann, J., Connor, R.C., Tyack, P.L., Whitehead, H. (eds.) Cetacean Societies. Field Studies of Dolphins and Whales. The University of Chicago Press. London, 433 pp.

Clapham , P.J., Baker, C.S. (2002) Modern whaling. In: Perrin , W.F., Würsig, B., Thewissen, J.G .M. (eds.) Encyclopedia of Marine Mammals. Academic Press, New York, 1414 pp.

Clapham, P.J., Mead, J.J. (1999) *Megaptera novaeangliae*. Mammalian Species, no. 604. 1-9.

Clapham, P., Young, S., Brownell, Jr., R. (1999) Baleen Whales: Conservation Issues and The Status Of The Most Endangered Populations. Publications, Agencies and Staff of the U.S. Department of Commerce. Paper 104.

Clapham, P.J., Aguilar, A., Hatch, L.T. (2008) Determining spatial and temporal scales for management: lessons from whaling. Mar. Mam. Sci., 24: 183–201.

Clapham, P.J., Baraff, L.S, Carlson, C.A., Christian, M.A., Mattila, D.K., Murphy, M.A., Pitman, S. (1993) Seasonal occurrence and annual return of humpback whales, *Megaptera novaeangliae*, in the southern Gulf of Maine. Can. J. Zool., 71: 440-443.

Clark, C.W. (1995) Matters arising out of the discussion of blue whales. Rep. Int. Whal. Comm., 45: 210–212.

Clark, C.W. (1993) Bioacoustics of baleen whales: From infrasonics to complex songs. Abstract. J. Acoust. Soc. Am., 94: 1830.

Clark, C.W. (1990) Acoustic behavior of mysticete whales. In: Thomas, J., Kastelein, R. (eds.) Sensory Abilities of Cetaceans. Plenum Press, New York, NY, 710 pp.

Clark, C.W. (1989) Call tracks of bowhead whales based on call characteristics as an independent means of determining tracking parameters Rep. Int. Whal. Comm., 39: 111-112.

Clark, C.W., Ellison, W.T., Southall, B.L., Hatch, L., Van Parijs, S.M., Frankel, A., Ponirakis, D. (2009) Acoustic masking in marine ecosystems: intuitions, analysis, and implication. Mar. Ecol. Prog. Ser., 395: 201-222.

Cranford, T.W., Krysl, P. (2015) Fin Whale Sound Reception Mechanisms: Skull Vibration Enables Low-Frequency Hearing. Plos one, Doi:10.1371/journal.pone.0116222.

Christiansen, F., Bertulli, C.G., Rasmussen, M.H., Lusseau, D. (2015) Estimating Cumulative Exposure of Wildlife to Non-Lethal Disturbance Using Spatially Explicit Capture–Recapture Models. J. Wildl. Manage., 79(2): 311-324. Doi: 10.1002/jwmg.836.

Christiansen, F., Rasmussen, M.H., Lusseau D. (2014) Inferring energy expenditure from respiration rates in minke whales to measure the effects of whale watching boat interactions. J. Exp. Mar. Biol. Ecol., 459: 96-104. Doi: http://dx.doi.org/10.1016/j.jembe.2014.05.014.

Christiansen, F., Rasmussen, M.H., Lusseau D. (2013*a*) Whale watching disrupts feeding activities of minke whales on a feeding ground. Mar. Ecol. Prog. Ser., 478: 239-251.

Christiansen, F., Rasmussen, M.H., Lusseau, D. (2013*b*) Inferring activity budgets in wild animals to estimate the consequences of disturbances. Behav. Ecol. 24, 1415–1425.

Chittleborough, R.G. (1965) Dynamics of two populations of the humpback whale, *Megaptera novaeangliae* (Borowski). Aust. J. Mar. Freshw. Res., 16: 33-128.

Chittleborough, R.G. (1958) The breeding cycle of the female humpback whale, *Megaptera nodosa* (Bonnaterre). Aust. J. Mar. Freshw. Res., 9: 1-18.

Cocker, P. (2008) Observations of ocean ambient noise (10 Hz to 10 kHz) at the site of a former navy listening station to the west of Point Sur, California, from January to July of 2007. Masters of Science, Naval Postgraduate School, Monterey, CA.

Constantine, R. (2001) Increased avoidance of swimmers by wild bottlenose dolphins (*Tursiops truncates*) due to long-term exposure to swim-with-dolphin tourism. Mar. Mam. Sci., 17(4): 689-702.

Constantine, R., Brunton, D. H., Dennis, T. (2004) Dolphin-watching tour boats change bottlenose dolphin (*Tursiops truncatus*) behaviour. Biol. Cons., 117: 299-307.

Corbett, J.J., Windebrake, J.J (2008) International trade and global shipping. In: Gallagher, K.P. (edt.) Handbook on Trade and the Environment (Elgar Original Reference). Edward Elgar Publishing, Cheltenham, Northampton, MA., 368 pp.

Corkeron, P.J., Connor, R.C. (1999) Why do Baleen whales migrate? Mar. Mam. Sci.,15(4): 1228-1245.

Craig, R.K. (2009) Beyond Winter v. NRDC: A Decade of Litigating the Navy's Active SONAR Around the Environmental Exemptions, 36 B.c. Envtl. Aff.L.Rev., 36(2): 353-378.

Craig, A.S., Herman, L.M. (1997) Sex differences in site fidelity and migration of humpback whales (*Megaptera novaeangliae*) to the Hawaiian Islands. Can. J. Zool., 75:1923-1933.

Croll, D.A., Clark, C.W., Acevedo, A., Tershy, B.R., Flores, S., Gedamke, J., Urban, J. (2002) Only male fin whales sing loud songs. Nature (London): 417: 809.

Croll, D.A., Clark, C.W., Calambokidis, J., Ellison, W.T., Tershy, B.R. (2001) Effect of anthropogenic low-frequency noise on the foraging ecology of *Balaenoptera* whales. Animal conservation, 4: 13-27.

Cummings, W.C., Thompson, P.O. (1971) Underwater sounds from the blue whale, *Balaenoptera musculus*. J. Acoust. Soc. Am., 50: 1193-1198.

Curry, B.E. (1999) Stress in mammals: the potential influence of fishery-induced stress on dolphins in the eastern tropical Pacific Ocean. NOAA Tech Memo NMFS-SWFSC-260, NOAA, La Jolla.

Dahl, P.H., Miller, J.H., Cato, D.H., Andrews, R.K. (2007) Ambient Noise Under Water and in Air. Acoustics Today, A publication of the Acoustical Society of America, 3(1): 23-33.

Dalla Rosa, L., Secchi, E.R., Maia, Y.G., Zerbini, A.N., Heide-Jørgensen, M.P. (2008) Movements of satellite-monitored humpback whales on their feeding ground along the Antarctic Peninsula. Polar Biol., 31: 771-781.

Dawbin, W.H. (1997) Temporal segregation of humpback whales during migration in Southern Hemisphere waters. Mem. Queensl. Mus.42(1): 105-38.

Dawbin, W.H. (1966) The seasonal migratory cycle of humpback whales. In: Norris, K. (edt.) Whales, dolphins and porpoises. University of California Press, Berkeley, 789 pp.

Dawbin, W. H. (1956). The migrations of humpback whales which pass the New Zealand Coast. Trans. Roy. Soc. New Zealand, 84: 147-196.

Deecke, V.B., Slater, P.J.B., Ford, J.K.B. (2002) Selective habituation shapes acoustic predator recognition in harbour seals. Nature, 420: 171–173. Doi:10.1038/nature01030.

Dill, L.M. (1974*a*) The escape response of the zebra danio (Brachydanio rerio). I. The stimulus for escape. Anim. Behav., 22: 711-722.

Dill, L.M. (1974*b*) The escape response of the zebra danio (Brachydanio rerio). II. The effect of experience. Anim. Behav., 22: 723-730.

Dolman, S.J., Weir, C.R., Jasny, M. (2009) Comparative review of marine mammal guidance implemented during naval exercises. Marine Poll. Bull., 58: 465-477.

Dransfield, A., Hines, E., McGowan, J., Holzman, B., Nur, N., Elliot, M., Howar, J., Jahncke, J. (2014) Where the whales are: using habitat modeling to support changes in shipping regulations within National Marine Sanctuaries in Central California. Endang. Species Res., 26: 39-57.

Eckart, C. (1946) Principles of Underwater Sound. Division 6, Volume 7. University of California (1868-1952), [Washington, D.C.]: Reprinted and distributed by the Research Analysis Group, Committee on Undersea Warfare, NOR, 295 pp.

Edds-Walton, P.L. (1997) Acoustic Communication Signals of Mysticete Whales. Bioacoustics, 8: 47-60.

Ekdale, E.G., Berta, A., Deméré, T.A. (2011) The Comparative Osteology of the Petrotympanic Complex (Ear Region) of Extant Baleen Whales (Cetacea: Mysticeti). Plos one. Doi: 10.1371/journal.pone.002131.

Ellison, W.T., Clark, C.W., Bishop, G.C. (1987) Potential use of surface reverberation by bowhead whales, *Balaena mysticetus*, in under-ice navigation: preliminary considerations. Rep. Int. Whal. Comm., 37: 329-332.

Emery, L. (2000) Data base description (DBD) for the variable-resolution, historical temporal shipping data base (HITS-V), version 1.1, p. 28-29 In: ONR PSI Technical Report TR-S-279. In: Mazucca, L.L. (2001) Potential Effects of Low Frequency Sound (LFS) from Commercial Vessels on Large Whales. University of Washington.

Erbe, C. (2013) International regulation of underwater noise. Acoust. Aust., 41(1): 12-19.

Erbe, C. (2002) Hearing Abilities of Baleen Whales. DRDC Atlantic, CR 2002-065.

Erbe, C., Farmer, D.M. (2000) Zones of impact around icebreakers affecting beluga whales in the Beaufort Sea. J. Acoust. Soc. Am., 108(3): 1332-1340.

Ewing, M., Worzel, J.L. (1948) Long-range Sound Transmission. Geol. Soc. Am. Mem., 27, Part III.

Félix, F., Haase, B. (2001) The humpback whale off The Coast of Ecuador, population parameters and behavior. Revista de Biología Marina y Oceanografía, 36(1): 61 – 74.

Finneran, J.J., Schlundt, C.E., Carder, D.A., Clark, J.A., Young, J.A., Gaspin, J.B., Ridgway, S.H. (2000) Auditory and behavioural responses of bottlenose dolphins (*Tursiops truncates*) and a beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions. J. Acoust. Soc. Am, 108:417-431.

Ford, J.K.B., Reeves, R.R. (2008) Flight or flight: antipredator strategies of baleen whales. Mammal Rev., 38(1): 50-86.

Fraker, P. N., Fraker. M. A. (1981) The 1980 whale monitoring program, Mackenzie Estuary. Report from LGL Ltd., Sidney, B.C., for Esso Resources Canada Ltd., Calgary, Alb., 98 pp.

Frid, A., Dill, L. (2002) Human-caused Disturbance Stimuli as a Form of Predation Risk. Conserv. Ecol., 6(1): [online] URL: http://www.consecol.org/vol6/iss1/art11.

Gambell, R. (1985) Fin whale *Balaenoptera physalus* (Linnaeus, 1758). In: Ridgway, S.H., Harrison, E. (eds.) Handbook of marine mammals, Vol. 3. Academic Press, London. In Reeves, R.R:, Silber, G.K., Payne, P.M. (1998) Draft recovery plan for the fin whale *Balaenoptera physalus* and sei whale *Balaenoptera borealis*. Office of Protected Resources, NMFS, NOAA, Silver Spring, MD. 65 pp.

Gaskin, D.E. (1976) The Evolution, Zoogeography, and Ecology of Cetacea. Oceanog. and Mar. Biol: Annual Review, 14: 247-346.

Geraci, J.R., Anderson, D.M., Timperi, R.J., Aubin, D.J., Early, G.A., Prescott, J.H., Mayo, C.A. (1989) Humpback whales (*Megaptera novaeangliae*) Fatally Poisoned by Dinoflagellate Toxin. Can. J. Fish. Aquat. Sci., 46: 1895-1898.

Gerrodette, T., Forcada, J. (2005) Non-recovery of two spotted and spinner dolphin populations in the eastern tropical Pacific Ocean. Mar. Ecol. Prog. Ser., 291: 1-21.

Gerrodette T, Gilmartin W.G. (1990) Demographic consequences of changed pupping and hauling sites of theHawaiian monk seal. Conserv. Biol., 4: 423–430.

Gerstein, E.R., Blue, J.E., Forysthe, S.E. (2005) The Acoustics of Vessel Collisions with Marine Mammals. OCEANS, 2005. Proceedings of MTS/IEEE 2: 1190-1197.

George, J.C., Clark, C.W., Carroll, G.M., Ellison, W.T. (1989) Observations on the Ice-Breaking and Ice Navigation Behavior of Migrating Bowhead Whales (*Balaena mysticetus)* near Point Barrow, Alaska, Spring 1985. Arctic, 42(1): 24-30.

Gill, J.A. (2007) Approaches to measuring the effects of human disturbance on birds. Ibis, 149 (Suppl. 1): 9-14.

Gill, J.A., Norris, K.N., Sutherland, W.J. (2001) Why behavioural responses may not reflect the population consequences of human disturbance. Biol. Cons., 97:265-268.

Goldbogen, J.A., Southall, B.L., DeRuiter, S.L., Calambokidis, J., Friedlaender, A.S., Hazen, E.L., Falcone, E.A., Schorr, G.S., Douglas, A., Moretti, D.J., Kyburg, C., McKenna, M.F., Tyack, P.L. (2013) Blue whales respond to simulated mid-frequency military sonar. Proc. R. Soc., 280: 20130657.

Goldbogen, J.A., Calambokidis, J., Oleson, E., Potvin, J., Pyenson, N.D., Schorr, G., Shadwick, R.E. (2011) Mechanics, hydrodynamics and energetics of blue whale lunge feeding: efficiency dependence on krill density. J. Exp. Biol. (214): 131–146. Doi:10.1242/jeb.048157.

Gordon, J.C.D., Gillespie, D., Potter, J., Frantzis, A., Simmonds, M.P., Swift, R., Thompson, D. (2005) A Review of the Effects of Seismic Survey on Marine Mammals. Mar. Technol. Soc. J., 37(4): 14-32.

Gray, L.M., Greeley D.S. (1980) Source level model for propeller blade rate radiation for the world's merchant fleet. J. Acoust. Soc. Am., 67: 516–522.

Greene CR Jr (1987) Characteristics of oil industry dredge and drilling sounds in the Beaufort Sea. J. Acoust. Soc. Am., 82: 1315–1324.

Gunther, E.R. (1949) The habits of fin whales. Discovery Rep. 25: 115-141.In: Richardson, W.J., Greene, Jr., C.R., Malme, C.I. & Thompson, D.H. (1995) Marine mammals and noise. Academic Press, New York, 576 pp.

Hall, C.M., Saarinen, J. (2010) Tourism and change in Polar Regions: climate, environments and experiences. Routledge, London, 318 pp.

Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, Bruno, J.F., Casey, K.S., Ebert, C., Fox, H.E., Fujita, R., Heinemann, D., Lenihan, H.S., Madin, E.M.P., Perry, M.T., Selig, E.R., Spalding, M., Stencke, R., Watson, R. (2008) A Global Map of Human Impact on Marine Ecosystems. Science, 319(5865): 948-952.

Hatch, L., Clar, C., Merrick, R., Van Parijs, S., Ponirakis, D., Schwehr, K., Thompson, Wiley, D. (2008) Characterizing the Relative Contribution of Large Vessels to Total Ocean Noise Fields: A Case Study Using the Gerry E. Studds Stellwagen Bank National Marine Sanctuary. Environ. Manage., 42: 735–752.

Hatch, L.T., Wright, A.J. (2007) A brief review of anthropogenic sound on the oceans. J. Comp. Physiol., 20: 121-133.

Heckel, G., Schramm, Y. (2005) Pers. Comm. In: Ford, J.K.B., Reeves, R. R. (2008) Flight or flight: antipredator strategies of baleen whales. Mammal Rev., 38(1): 50-86.

Heitmeyer, R.M., Wales, S.C., Pflug, L.A (2003) Shipping Noise Predictions: Capabilities and Limitations. Mar. Techno. Soc. J., 37(4): 54-65. Doi: http://dx.doi.org/10.4031/002533203787537023.

Helweg, D.A., Herman, L.M. (1994) Diurnal Patterns of Behaviour and Group Membership of Humpback whales (*Megaptera novaeangliae*) Wintering in Hawaiian Waters. Ethol., 98: 298-311.

Highham, J.E.S, Lusseau, D. (2007) Urgent Need for Empirical Research into Whaling and Whale Watching. Conserv. Biol., 21(2): 554-558.

Hildebrand, J.A. (2009) Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser., 395: 5-20.

Hildebrand, J.A. (2005) Impacts of Anthropogenic Sound. In: Reynolds III, J.E., Perrin, W.F., Reeves, R.R:, Montgomery, S., Ragen, T.J. (eds.) Marine Mammal Research: Conservation beyond Crisis. The Johns Hopkins University Press, Baltimore, MD, 240 pp.

Ingmanson, D.E., Wallace, W.J. (1973) Oceanology: An Introduction. Wadsworth Publishing Co., Belmont, CA. In: Wartzok, D. & Ketten, D.R. (1999) Marine mammal sensory systems. In: Reynolds, J., Rommel, S. (eds.) Biology of marine mammals. Smithsonian Institution Press, Washington, DC, 600 pp.

Ingebrigtsen, A. (1929) Whales caught in the North Atlantic and other seas. Rapp. Proc. Verb. Cons. Int. Explor. Mer., 56: 1-26.

International Maritime Organization (2014) Guidelines for the reduction of underwater noise from commercial shipping to address adverse impacts on marine life. MEPC.1/Circ.833.

International Maritime Organization (2013) Provisions for reduction of noise from commercial shipping and its adverse impacts on marine life. IMO Subcommittee on Ship Design and Equipment. DE 57/WP.8.

International Maritime Organization (2009) Noise from Commercial Shipping and its Adverse Impacts on Marine Life, Report from the Correspondence Group (MEPC59/19/1).

International Union for Conservation of Nature (2014) The IUCN Red List of Threatened Species. Version 2014.3. <www.iucnredlist.org>. Downloaded on 21 December 2014.

International Union for Conservation of Nature (2004) Undersea Noise Pollution. Resolution RESWCC3.068. World Conservation Congress, Bangkok, Thailand, 17-25 November 2004. 3 pp.

Irving, L. (1972) Arctic life of birds and mammals. Springer, Berlin, 212 pp.

International Whaling Commission (2005) Report of the scientific committee. Annex K. Report of the Standing Working Group on environmental concerns. J. Cetacean Res. Manag., 7(Suppl.): 267–305.

International Whaling Commission (1994) Report of the workshop on mortality of cetaceans in passive fishing nets and traps. In: Perrin, W.F., Donovan, G., Barlow, J. (eds.) Gillnets and cetaceans: Incorporating the proceedings of the symposium and workshop on the mortality of cetaceans in passive fishing nets and traps. Reports of the International Whaling Commission, special issue 15: 6-71. Cambridge, International Whaling Commission.

Jackson, J.A., Steel, D.J., Beerli, P., Congdon, B.C., Olavarría, C., Leslie, M.S., Pomilla, C., Rosenbaum, H., Baker, C.S. (2014) Global diversity and oceanic divergence of humpback whales (*Megaptera novaeangliae*). Proc. R. Soc. Doi: 10.1098/rspb.2013.3222.

Jakobson, L. (2010) China Prepares for an Ice-Free Arctic. SIPRI Insights on Peace and Security, 2, D14209. Doi:10.1029/2009JD013795.

Jensen, F.B., Kuperman, W.A., Porter, M.B., Schmidt, H. (1994) Computational Ocean Acoustics. AIP Press, New York, NY, 794 pp.

Johnson, J.S. (2003) SURTASS LFA environmental compliance experience. Presentation at ECOUS (Environmental Consequences of Underwater Sound), San Antonio, Texas, 12–16 May 2003. In: Weilgart, L. (2007) Impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool., 85: 1091-1116.

Johnson, C.S. (1967) Sound detection thresholds in marine mammals. In: Tavolga, W.N. (edt.) Marine Bioacoustics, Vol. 2, Pergamon, New York, 413 pp.

Kasamatsu, F., Joyce, G.G., Ensor, P., Memorez, J. (1996) Current occurence of baleen whales in Antarctic waters. Rep. Int. Whal. Comm., 46: 293-303.

Kawamura, A. (1980) A review of food of balaenopterid whales. Sci. Rep. Whales. Res. Inst.. 32: 155-197.

Ketten, D.R. (2002) Marine Mammal Auditory Systems: A Summary of Audiometric and Anatomical Data and Implications for Underwater Acoustic Impacts. Polarforschung, 72(2/3): 79-92.

Ketten, D.R. (2000) Cetacean ears. In: Au, W.W.L., Popper, A.N., Fay, R.R. (eds.) Hearing by Whales and Dolphins. Springer, New York, 485 pp.

Ketten, D.R. (1997) Structure and Function in Whale Ears. Bioacoustics, 8: 103-135.

Ketten, D.R. (1995) Estimates of blast injury and acoustic trauma zones for marine mammals from underwater explosions. In: Kastelein R.A., Thomas, J.A., Nachtigall, P.E. (eds.) Sensory Systems of Aquatic Mammals. De Spil Publishers, Woerden, 588 pp.

Ketten, D.R. (1994) Functional Analyses of Whale Ears: Adaptations for Underwater Hearing. Doi: 10.1109/OCEANS.1994.363871.

Ketten, D.R. (1992) The Marine Mammal Ear: Specializations for Aquatic Audition and Echolocation. In: Webster, D.B., Fay, R.R., Popper, A.N. (eds.) The Evolutionary Biology of Hearing. Springer, New York, NY, 859 pp.

Ketten, D.R.. Wartzok, D. (1990) Three-dimensional reconstructions of the dolphin ear. In: Thomas, J., Kastelein, R. (eds.) Sensory abilities of cetaceans. Plenum Press, New York, 710 pp.

Ketten, D.R., Lien, J., Todd, S. (1993) Blast injury in humpback whale ears. Evidence and implications. J. Acoust. Soc. Am., 94: 1849.

Kinsler, L.E., Frey, A.R., Coppens, A. B., Sanders, J. V. (1982) Fundamentals of Acoustics, 3rd Edition. John Wiley & Sons, New York, NY, 560 pp.

Laist, D.W., Knowlton, A.R., Mead, J.G., Collet, A.S., Podesta, M. (2006) Collisions between ships and whales. Mar. Mam. Sci., 17(1): 35-75.

Lambertsen, R.H. (1983) Internal mechanism of rorqual feeding. J. Mammal. 64: 76-88.

Lamers, M., Haase, D., Amelung, B. (2008) Facing the elements: analysing trends in Antarctic tourism. Tour. Rev., 63(1): 15-27.

Leaper, R., Renilson, M. (2012) A review of practical methods for reducing underwater noise pollution from large commercial vessels. Int. J. Marit. Engin., 154: A79-A88. Doi: 10.3940/rina.ijme.2012.a2.227.

Lerczak, J.A., Hobbs, R.C. (1998) Calculating sighting distances from angular readings during shipboard, aerial, and shore-based marine mammal surveys. Mar. Mam. Sci., 14(3): 590-599.

LGL & Mai (2011) Environmental Assessment of Marine Vibroseis. LGL Rep. TA4604-1; JIP contract 22 07-12. Rep. from LGL Ltd., environ. res. assoc., King City, Ont., Canada, and Marine Acoustics Inc., Arlington, VA, U.S.A., for Joint Industry Programme, E&P Sound and Marine Life, Intern. Assoc. of Oil & Gas Producers, London, U.K. 207 pp.

Ljungblad, D.K., Thompson, P.O., Moore, S.E. (1982) Underwater sounds recorded from migrating bowhead whales, *Balaena mysticetus* in 1979. Acoust. Soc. Am., 71: 477-478.

Lockyer, C. (1981) Growth and energy budgets of large baleen whales from the Southern Hemisphere. p. 379-487. In: Food & Agric. Organiz. of the United Nations. Mammals in the seas. FAO Fish. Ser. No. 5, vol. 3, Rome, 504 pp.

Lucke, K., Lepper, P.A., Blanchet, M., Siebert, U. (2011) The use of an air bubble curtain to reduce the received sound levels for harbor porpoises (*Phocoena phocoena*). J. Acoust. Soc. Am., 130(5): 3406–3412.

Lurton, X. (2002) An Introduction to Underwater Acoustics. Principles and Applications. Springer, Chichester, 347 pp.

Lusseau, D., Bain, D.E., Williams, R., Smith, J.C. (2009) Vessel traffic disrupts the foraging behaviour of southern resident killer *whales Orcinus orca*. Endang. Species Res., 6: 211-221.

Lusseau, D. (2003) How do tour boats affect the behavioral state of bottlenose dolphins (*Tursiops sp.*)? Applying Markov chain modeling to the field study of behavior. Conserv. Biol., 17: 1785–1793.

Mann, J. (2000) Unraveling the Dynamics of Social Life. Long-term Studies and Observational Methods. In: Mann, J., Connor, R.C., Tyack, P.L., Whitehead, H. (eds.) Cetacean Societies. Field Studies of Dolphins and Whales. The University of Chicago Press. London, 433 pp.

Mayr, E. (1965) Animal species and evolution. Belknap Press, Cambridge, MA, 459 pp.

McCarthy, E. (2004) International Regulation of Underwater Sound: Establishing Rules and Standards to Address Ocean Noise Pollution. Kluwer Academic Publishers, Boston, MA, 295 pp.

McDonald, M.A., Hildebrand, J.A., Wiggins, S.M. (2006) Increases in deep ocean ambient noise in the Northeast Pacific west of San Nicolas Island, California. J. Acoust. Soc. Am., 120(2): 711-718.

McDonald, M.A., Hildebrand, J.A., Webb, S.C. (2005) Blue and fin whales observed on a seafloor array in the Northeast Pacific. J. Acoust. Soc. Am., 98(2): 712-721.

McDonald, M.A., Calambokidis, J., Teranishi, A.M., Hildebrand, J.A. (2001) The acoustic calls of blue whales off California with gender data. J. Acoust. Soc. Am., 109: 1728–1735.

Mehta, A.V., Allen, J.M., Constantine, R., Garrigue, C., Jann; B., Jenner, C., Marx, M.K., Matkin, C.O., Mattila, D.K., Minton, G., Mizroch, S.A., Olavarría, C., Robbins, J., Russell, K.G., Seton, R.E., Steiger, G.H., Víkingsson, G.A., Wadell, P.R., Witteveen, B.H., Clapham, P.J. (2007) Baleen whales are not important as prey for killer whales *Orcinus orca* in high-latitude regions. Mar. Ecol. Prog. Ser., 348: 297-307.

Marine Mammal Commission (2007) Marine Mammals and Noise: A Sound Approach to Research and Management. A Report to the US Congress from the Marine Mammal Commission. Bethesda, MD: U.S. Marine Mammal Commission.

Morton, A. B., Symonds, H. K. (2002) Displacement of *Orcinus orca* (L.) by high amplitude sound in British Columbia, Canada. – ICES J. of Mar. Sci., 59: 71–80.

Munk, W.H., O'Reilly, W.C., Reid, J.L. (1988) Australia-Bermuda Sound Transmission Experiment (1960) Revisited. J. Phys. Ocean., 18: 1876-1898.

Nachtigall, P.E., Pawlowski, J., Au, W.W.L. (2003) Temporary threshold shifts and recovery following noise exposure in the Atlantic bottlenosed dolphin (*Tursiops truncatus*). J. Acoust. Soc. Am., 113: 3245-3429.

National Marine Fisheries Service (1991) Recovery Plan for the northern right whale (*Eubalaena glacialis*). Silver Spring. MD: National Marine Fisheries Service.

National Oceanic and Atmospheric Administration (2004) Final Report of the National Oceanic and Atmospheric Administration (NOAA) International Symposium: "Shipping Noise and Marine Mammals: A Forum for Science, Management, and Technology". Arlington, VA.

National Research Council (2005) Marine Mammal Populations and Ocean Noise: Determining When Noise Causes Biologically Significant Effects. The National Academies Press, Washington, DC.

National Research Council (2003) Ocean Noise and Marine Mammals. The National Academies Press, Washington, DC.

National Research Council (1995) NRC Annual Report 1994-95. Ottawa: NRC.

Nemoto, T. (1970) Feeding patterns of baleen whales in the oceans. In: Steele, J. H. (edt.) Marine food chains. University of California Press, Berkeley and Los Angeles, 552 pp.

Nishiwaki, M. (1950) On the body weights of whales. Sci. Rep. Whales. Res. Inst., 4: 184-209.

Notarbartolo-di-sciara, G. (1987) Killer whale, *Orcinus orca*, in the Mediterranean Sea. Mar. Mam. Sci., 3: 356–360.

Nowacek, D.P., Thorne, L.H., Johnston, D.W., Tyack, P.L. (2007) Responses of cetaceans to anthropogenic noise. Mammal Rev., 37(2): 81-115.

Nowacek, D.P., Johnson, M.P., Tyack, P. (2004) North Atlantic right whales (*Eubalaena glacialis*) ignore ships but respond to alerting stimuli. Proc. R. Soc., 271: 227–231. Doi: 10.1098/rspb.2003.2570.

O'Shea, T.J., Brownell, Jr., R.L. (1994) Organochlorine and metal contaminants in baleen whales: a review and evaluation of conservation implications. Sci. Total Environ., 154: 179–200.

Oleson, E.M., Calambokidis, J., Burgess, W.C., McDonald, M.A., LeDuc, C.A., Hildebrand, J.A. (2007) Behavioral context of Northeast Pacific blue whale call production. Mar. Ecol. Prog. Ser., 330: 269–284.

Owen K. 2014. The feeding behaviour of humpback whales while on migration: methods, driving factors and its importance to whale ecology. PhD thesis.

Palsbøll, P.J., Bérubé, M., Aguilar, A., Notarbartolo-di-Sciara, G., Nielsen, R. (2004) Discerning between recurrent gene flow and recent divergence under a finite-site mutation model applied to North Atlantic and Mediterranean fin whales *Balaenoptera physalus* populations. Evol., 58: 670–675.

Paterson, R., Paterson, P., Cato, D.H. (1994) The status of humpback whales *Mageptera novaeanglia* in East Australia thirty years after whaling. Biol. Cons., 70: 135-142.

Payne, R.S., McVay, S. (1971) Songs of humpback whales. Science, 173: 585-597.

Payne, R., Webb, D. (1971) Orientation by means of long range acoustic signaling in baleen whales. Ann. NY Acad. Sci., 188 (1971): 110-141.

Payne, P.M., Wiley, D.N., Young, S.B., Pittman, S., Clapham, P.J., Jossi, J.W. (1990) Recent fluctuations in the abundance of baleen whales in the southern Gulf of Maine in relation to changes in selected prey. Fishery Bulletin, 88: 687–696. In: Clapham, P., Young, S., Brownell, Jr., R. (1999) Baleen Whales: Conservation Issues and The Status Of The Most Endangered Populations. Publications, Agencies and Staff of the U.S. Department of Commerce. Paper 104.

Pepper, P.A., Turner, V.L.G., Goodson, A.D., Black, K.D. (2004) Source levels and spectra emitted by three commercial aquaculture anti-predation devices. In: Simons, D.G., Blacquiere, G. (eds.) Proc 7th European Conf on Underwater Acoustics, ECUA 2004. Commission of the European Communities, Delft.

Pivorunas, A. (1979) The feeding mechanisms of baleen whales. Am. Sci., 67: 432–440.

Ralls, K. (1976) Mammals in which females are larger than males. Q. Rev. Bio., 51(2): 245-278.

Reeves, R.R:, Silber, G.K., Payne, P.M. (1998) Draft recovery plan for the fin whale *Balaenoptera physalus* and sei whale *Balaenoptera borealis*. Office of Protected Resources, NMFS, NOAA, Silver Spring, MD, 65 pp.

Reidenberg, J.S., Laitman, J.T. (2007) Discovery of a low frequency sound source in Mysticeti (baleen whales): anatomical establishment of a vocal fold homolog. Anat. Rec., 290(6): 745-759.

Reilly, S.B., Bannister, J.L., Best, P.B., Brown, M., Brownell Jr., R.L., Butterworth, D.S., Clapham, P.J., Cooke, J., Donovan, G.P., Urbán, J., Zerbini, A.N. (2013) *Balaenoptera physalus*. The IUCN Red List of Threatened Species. Version 2014.3. <www.iucnredlist.org>. Downloaded on 21 December 2014.

Reilly, S.B., Bannister, J.L., Best, P.B., Brown, M., Brownell Jr., R.L., Butterworth, D.S., Clapham, P.J., Cooke, J., Donovan, G.P., Urbán, J. & Zerbini, A.N. (2008) *Megaptera novaeangliae*. The IUCN Red List of Threatened Species. Version 2014.3. <www.iucnredlist.org>. Downloaded on 21 December 2014.

Renilson, M.R., Leaper, R.C., Boisseau, O. (2012) Practical techniques for reducing the underwater noise pollution generated by commercial ships. Proceedings of the International Conference on the Environmentally Friendly Ship, Royal Institution of Naval Architects, February 28-29, London.

Richardson, W.J., Greene, Jr., C.R., Malme, C.I., Thompson, D.H. (1995) Marine mammals and noise. Academic Press,New York, 576 pp.

Richardson, W.J., Würsig, B., Greene,,Jr., C.R. (1990) Reactions of bowhead whales, *Balaena mysticetus*, to drilling and dredging noise in the Canadian Beaufort Sea. Mar. Environ. Res., 29: 135-160.

Ridder, S.A:L., Biondi, B.L., Nichols, D. (2015) Elliptical-anisotropic eikonal phase velocity tomography. Geophys. Res. Lett. Doi: 10.1002/2014GL062805.

Risch, D., Gales, N.J., Gedamke, J., Kindermann, L., Nowacek, D.P., Read, A.J., Siebert. U., Van Opzeeland, I.C., Van Parijs, S.M., Friedlaender, A.S. (2014) Mysterious bio-duck sound attributed to the Antarctic minke whale (*Balaenoptera bonaerensis*). Biol. Lett., 10: 20140175. http://dx.doi.org/10.1098/rsbl.2014.0175.

Rolland, R.M., Parks, S.E., Hunt, K.E., Castellote, M., Corkeron, P.J., Nowacek, D.P., Wasser, S.K., Kraus, S.D. (2012) Evidence that ship noise increases stress in right whales. Proc. R. Soc. Doi: 10.1098/rspb.2011.2429.

Ross, D. (1976) Mechanics of Underwater Noise. Pergamon, New York, 375 pp. (Reprinted 1987, Peninsula Publishing, Los Altos, CA).

Schlund, C.E., Finneran, J.J., Carder, D.A., Ridgway, S.H. (2000) Temporary shift in masked hearing thresholds of bottlenose dolphins, *Tursiops truncatus*, and white whales, *Delphinapterus leucas*, after exposure to intense tones. J. Acoust. Soc. Am., 107: 3496-3508.

Sears, R., Perrin,W.F. (2009) Blue whale (Balaenoptera musculus). In: Perrin, W.F., Würsig, B., Thewissen, J.G.M (eds.) Encyclopedia of Marine Mammal. Second Edition. Academic Press, New York, 1352 pp.

Schevill, W.E., Watkins, W.A, Backus, R.H. (1964) The 20-cycle signals and *Balaenoptera* (fin whales). In: Tavolga, W.N. (edt.) Marine Bioacoustics. Pergamon, Oxford, 413 pp.

Širovic, A., Hildebrand, J.A., Wiggins, S. (2007) Blue and fin whale call source levels and propagation range in the Southern Ocean. J. Acoust. Soc. Am., 122(2): 1208-1215.

Širovic, A., Hildebrand, J.A., Wiggins, S.M., McDonald, M.A., Moore, S.E., Thiele, D. (2004) Seasonality of blue and fin whale calls and the influence of sea ice in the Western Antarctic Peninsula. Deep-Sea Res. PT II, 51: 2327-2344.

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, Jr., C.R., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., Tyack, P.L. (2007) Marine mammal noise exposure criteria: Initial scientific recommendations. Aquatic Mammals, 33: 411-521.

Stamation, K.A., Croft, D.B., Shaughnessy. P.D., Waples, K.A. (2007) Observations of Humpback Whales (*Megaptera novaeangliae*) Feeding During Their Southward Migration Along the Coast of Southeastern New South Wales, Australia: Identification of a Possible Supplemental Feeding Ground. Aquat. Mam., 33(2): 165-174. Doi: 10.1578/AM.33.2.2007.165

Stafford, K.M., Fox, C.G., Clark, D.S. (1998) Long-range acoustic detection and localization of blue whale calls in the northeast Pacific Ocean. J. Acoust. Soc. Am., 104: 3616–3625.

Stockin, K.A., Burgess, E.A. (2005) Opportunistic feeding of an adult male humpback whale (*Megaptera novaeangliae*) migrating along the coast of southeastern Queensland, Australia. Aquat. Mamm., 31(1): 120-123.

Stone, G., Flòrez-Gonzàlez L., Katina, S.K. (1990) Whale migration record. Nature, London, 346: 705.

Straley, J.M. (1990) Fall and winter occurrence of humpback whales (*Megaptera novaeangliae*) in southeastern Alaska. Rep. Int. Whal. Comm. (Special Issue 12): 319-323.

Swingle, W.M., Barco, S.G., Pitchford, T.D., McLellan, W.A., Pabst, D.A. (1993) Appearance of juvenile humpback whales feeding in the nearshore waters of Virginia. Mar. Mam. Sci., 9: 309-315.

Thiele, D., Chester, E.T., Gill, P.C. (2000) Cetacean distribution off Eastern Antarctica (80-150°E) during the Austral summer of 1995/1996. Deep-Sea Res. PT II, 47: 2543-2572.

Thomas, J., Chun, N., Au, W., Pugh, K. (1988) Underwater Audiogram of a False Killer Whale (*Pseudorca crassidens)*. J. Acoust. Soc. Am., 84: 936-940.

Thompson, T.J., Winn, H.E., Perkins, P.J. (1979) Mysticete sounds. In: Winn, H.E., Olla, B.L. (eds.) Behaviour of marine mammals .Vol. 3: Cetaceans. Springer, New York, 438 pp.

Trites, A.W., Christensen, V., Pauly, D. (1997) Competition between Fisheries and Marine Mammals for Prey and Primary Production in the Pacific Ocean. J. North. Atl. Fish. Sci., 22: 173-187.

Tyack, P.L. (2002) Functional Aspects of Cetacean Communication. In: Mann, J., Connor, R.C., Tyack, P.L., Whitehead, H. (eds.) Cetacean Societies. Field Studies of Dolphins and Whales. The University of Chicago Press. London, 433 pp.

Tyack, P.L. (1993) Reactions of bottlenoise dolphins, Tursiops truncatus, and migrating gray whales, Eschrichtius robustus, to experimental playback of low-frequency man-made noise. J. Acoust. Soc. Am., 94(3): 1830.

Tyack, P., Whitehead, H. (1983) Male competition in large groups of wintering humpback whales. Behav., 83:132–154.

United Nations Division for Ocean Affairs and the Law of the Sea (1982) United Nations Convention on the Law of the Sea (UNCLOS).

Urick, R.J. (1983) Principles of Underwater Sound. McGraw-Hill Co, New York, NY.

Van Opzeeland, I., Van Parijs, S., Kindermann, L., Burkhardt, E., Boebel, O. (2013) Calling in the Cold: Pervasive Acoustic Presence of Humpback Whales (Megaptera novaeangliae) in Antarctic Coastal Waters. Plos one. Doi: 10.1371/journal.pone.0073007.

Walther, F.R. (1969) Flight behaviour and avoidance of predators in Thomson's gazelle (*Gazella thomsoni*: Guenther 1884). Behaviour 34: 184-221.

Wartzok, D., Ketten, D.R. (1999) Marine mammal sensory systems. In: Reynolds, J., Rommel, S. (eds.) Biology of marine mammals. Smithsonian Institution Press, Washington, DC, 600 pp.

Watkins, W.A., Schevill, W.E. (1979) Aerial observation of feeding behavior in four baleen whales: *Eubalaena glacialis, Balaenoptera borealis*, *Megaptera novaeangliae*, and *Balaenoptera physalus*. J. Mammal., 60: 155-163.

Watkins, W.A., Tyack, P., Moore, K.E., Bird, J.E. (1987) The 20-Hz signals of finback whales (*Balaenoptera physalus*). J. Acoust. Soc. Am., 82: 1901-1911.

Wenz GM (1969) Low-frequency deep-water ambient noise along the Pacific Coast of the United States. US Navy J. Underw. Acoust., 19: 423–444.

Wenz, G.M. (1968) Properties of deep-water, low-frequency, ambient noise west of San Diego, California. TP 39, Naval Undersea Warfare Center, San Diego, CA.

Wenz, G.M. (1962) Acoustic ambient noise in the ocean: spectra and sources. J. Acoust. Soc. Am., 34: 1936–1956.

Wenz, G.M. (1961) Periodic variations in low-frequency underwater ambient noise levels. Report 1014, Navy Electronic Laboratory, San Diego, CA.

Weilgart, L.S. (2007*a*) Impacts of anthropogenic ocean noise on cetaceans and implications for management. Can. J. Zool., 85: 1091-1116.

Weilgart, L.S. (2007*b*) A Brief Review of Known Effects of Noise on Marine Mammals. J. Comp. Physiol., 20: 159-168.

Weinrich, M.T. (1991) Stable social associations among humpback whales (*Megaptera novaeangliae)* in the southern Gulf of Maine. Can. J. Zool., 1991, 69(12): 3012-3019.

Weir, C.R., Dolman, S.J. (2007) Comparative Review of the Regional Marine Mammal Mitigation Guidelines Implemented during Industrial Seismic Surveys, and Guidance Towards a Worldwide Standard. J. Int. Wildl. Law Policy, 10:1-27.

Wever, E.G., McCormick, J.G., Palin, J., Ridgway, S.H. (1971) The Cochlea of the Dolphin, *Tursiops truncatus*: The Basilar Membrane. PNAS, USA, 67: 2707-2711.

Whitehead, H. (1983) Structure and stability of humpback whale groups off Newfoundland. Can. J. Zool., 61: 1391-1397.

Whitehead, H.P. (1981) The behavior and ecology of the humpback whale on the Northwest Atlantic. Ph.D. dissertation, Cambridge University, Cambridge. In: Clapham, P.J. (2000) The humpback whale. Seasonal Feeding and Breeding in a Baleen Whale. In: Mann, J., Connor, R.C., Tyack, P.L., Whitehead, H. (eds.) Cetacean Societies. Field Studies of Dolphins and Whales. The University of Chicago Press. London, 433 pp.

Whitehead, H., Mann, J. (2000) Female reproductive strategies of cetaceans. Life histories and Calf care. In: Mann, J., Connor, R.C., Tyack, P.L., Whitehead, H. (eds.) Cetacean Societies. Field Studies of Dolphins and Whales. The University of Chicago Press, London, 433 pp.

Whitehead, H., Reeves, R.R., Tyack, P.L. (2000) Science and the Conservation, Protection, and Management of Wild Cetaceans. In: Mann, J., Connor, R.C., Tyack, P.L., Whitehead, H. (eds.) Cetacean Societies. Field Studies of Dolphins and Whales. The University of Chicago Press, London, 433 pp.

Williams, R., Ashe, E. (2007) Killer whale evasive tactics vary with boat number. J. Zool., 272: 390-397.

Williams, R., Lusseau, D., Hammond, P.S. (2006) Estimating relative energetic costs of human disturbance to killer whales (*Orcinus orca*). Biol. Cons., 133: 301-311.

Williams, R., Trites, A. & Bain, D.E. (2002) Behavioural responses of killer whales (*Orcinus orca*) to whale-watching boats: opportunistic observations and experimental approaches. J. Zool., 256: 255–270.

Williams, Jr.,A.O., Horne, W. (1967) Axial Focusing of Sound on the SOFAR Channel. J. Acoust. Soc. Am., 41(1): 189-198.

Wright, A.J., Deak, T., Parsons, E.C.M. (2011) Size matters: management of stress responses and chronic stress in beaked whales and other marine mammals may require larger exclusion zones. Marine Poll. Bull., 63(1-4): 5–9.

Würsig, B., Greene, Jr., C.R., Jefferson, T.A. (2000) Development of an air bubble curtain to reduce underwater noise of percussive piling. Mar. Environ. Res., 49: 79-93.

Zimmer, W.M.X., Tyack, P.L. (2007) Repetitive shallow dives pose decompression risk in deep-diving beaked whales. Mar. Mam. Sci., 23: 888–925. Doi:10.1111/j.1748-7692.2007.00152.

Zitterbart, D.P. (2013): Locomotion in Biological Systems. PhD thesis. hdl:10013/epic.43639

Zitterbart, D.P., Kindermann, L., Burkhardt, E., Boebel, O. (2013) Automatic Round-the-Clock Detection of Whales for Mitigation from Underwater Noise Impacts. Plos one 8(8). Doi: 10.1371/journal.pone.0071217.

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Eidesstattliche Erklärung

Hiermit versichere ich, dass ich diese Arbeit selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel benutzt habe. Außerdem versichere ich, dass ich die allgemeinen Prinzipien wissenschaftlicher Arbeit und Veröffentlichung, wie sie in den Leitlinien guter wissenschaftlicher Praxis der Carl von Ossietzky Universität Oldenburg festgelegt sind, befolgt habe.

Hanna Michel