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Largest baleen whale mass mortality during strong El Niño event is likely related to harmful toxic algal bloom

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While large mass mortality events (MMEs) are well known for toothed whales, they have been rare in baleen whales due to their less gregarious behaviour. Although in most cases the cause of mortality has not been conclusively identified, some baleen whale mortality events have been linked to bio-oceanographic conditions, such as harmful algal blooms (HABs). In southern Chile, HABs can be triggered by the ocean-atmosphere phenomenon El Niño. The frequency of the strongest El Niño events is increasing due to climate change. In March 2015, by far the largest reported mass mortality of baleen whales took place in a gulf in southern Chile. Here we show that the synchronous death of at least 343, primarily sei, whales can be attributed to HABs during a building El Niño. Although considered an oceanic species, the sei whales died while feeding near to shore in previously unknown large aggregations. This provides evidence of new feeding grounds for the species. The combination of older and newer remains of whales in the same area indicate that MMEs have occurred more than once in recent years. Large HABs and reports of marine mammal MMEs along the north-east Pacific coast may indicate similar processes in both hemispheres. Increasing MMEs through HABs may become a serious concern in the conservation of endangered whale species.
INTRODUCTION

Although most populations of whales have been fully protected from industrial hunting for half a century, some were reduced to such low levels that recovery is still very slow (Baker & Clapham, 2004). Today, whales face additional threats, such as ship strikes, entanglement and by-catch, underwater noise, pollution and habitat loss (Clapham et al., 1999). Moreover, since ocean conditions directly influence quality and availability of the prey species of baleen whales, the effects of climate change will become a concern (Simmonds & Isaac, 2007).
Mass mortality events (MME) of marine mammals generally involve social species such as dolphins or sea lions, but are rare in baleen whales due to their less gregarious behaviour (Perrin et al., 2009a). When MMEs have occurred in baleen whales they have often extended over several months and large areas, involving mostly coastal whales (Table 1). In the Northeast Pacific, seven to eight times more gray whales (*Eschrichtius robustus*) washed ashore during the years 1999 and 2000 than is usual in such a time span. Of these, 106 died within a three-month period in Mexico (Gulland et al., 2005). In the course of 2012, 116 southern right whales (*Eubalaena australis*), mostly calves, washed ashore at their breeding ground in Valdés Peninsula, Argentina (Anonymous, 2015). During 2009, 46 humpback whales (*Megaptera novaeangliae*) stranded in Australia (Coughran et al., 2013) and 96 in Brazil during 2010, most of them calves and juveniles (Rowntree et al., 2013). Less frequent and much smaller in magnitude are sudden and locally restricted baleen whale mortalities. The largest of those involved 14 humpback whales which died around Cape Cod during five weeks in November 1987 (Geraci et al., 1989) (Table 1). The causes of most MMEs have not been conclusively identified (e.g. Anonymous, 2015; Coughran et al., 2013; Gulland et al., 2005); however, paralytic shellfish poisoning during harmful algal blooms (HABs) has been argued as one of the main likely causes (and this is also the case for other marine vertebrate mass mortalities; Geraci et al., 1989; Durbin et al., 2002; Doucette et al., 2006; Rowntree et al., 2013; Cook et al., 2015; D’Agostino et al., 2015; Wilson et al., 2015; Lefebre et al., 2016).
Harmful algal blooms have an extended record in southern Chile (particularly the genus *Alexandrium* with production of Paralytic Shellfish Toxins (PST)). HABs have been of concern to fishermen and Patagonian communities since at least 1972, when the first mass intoxication was recorded (Suárez and Guzmán, 2005). Since then, the geographic region in which blooms have been detected has increased to over 1000 km north-south extent (Molinet et al. 2003). HABs have also become more frequent, becoming annual events with blooms normally occurring in large areas during the summer and fall (Guzmán et al., 2002). Due to the danger posed by these toxins, the Chilean government funds a monitoring program with over 200 sampling stations throughout the southern part of Chile, where phytoplankton and shellfish samples are obtained and later analysed for the presence of microalgae and their toxins (paralytic shellfish toxin PST, amnesic shellfish toxin AST, diarrheic shellfish toxin DST) (Suárez and Guzmán, 2005). Unfortunately, mainly due to the difficulty accessing many sites, these biotoxin data are only available for a limited coastal area of southern Chile.
Chilean Patagonia is a complex environment that hosts one of the largest and most extensive fjord regions, with a north-south extent of approximately 1,500 km (42ºS to 55ºS), covering an area of over 240,000 km² and with a coastline of more than 80,000 km, made up of numerous fjords, channels and islands. At the same time this is one of the least scientifically understood marine regions of the world (Försterra, 2009; Försterra et al., in press). Precipitation can locally exceed 6,000 mm per year and the tidal range can exceed 7 m. The prevailing strong westerly winds make its exposed shores amongst the most wave-impacted in the world (Försterra, 2009). These factors are responsible for the inaccessibility of a large part of this region. Chilean Patagonia is subdivided into the North, Central and South Patagonian Zone (for a summary of biogeography of the region see Häussermann and Försterra, 2005 and Försterra et al., in press). The remote area around Golfo de Penas and Taitao Peninsula (Fig. 1) is situated in the Central Patagonian Zone between 47 ºS and 48ºS. Except for two Chilean Navy lighthouses at Cabo Raper and San Pedro, the closest human settlements are more than 200 km away (Tortel, Puerto Aysén and Puerto Edén).
In general, Chilean Patagonia is influenced by the West Wind Drift, a large-scale eastward (onshore) flow which diverges at the coast to form the northward Humboldt Current and the southward Cape Horn Current (Thiel et al., 2007). The fjordic nature of the coastline produces significant local complexity, with many inlets and dispersed freshwater sources. High productivity in these coastal waters (Fig. 2) is driven by the availability of both terrestrial nutrients, carried by large rivers originating at the Northern and Southern Patagonian Icefields, and marine nutrients (González et al., 2010; Torres et al., 2014). While this region experiences coastal winds that favor net coastal downwelling, intermittent and/or localized upwelling, in particular in summer and north of Taitao Peninsula (47°S), is expected to enhance the supply of marine nutrients to coastal waters, and the relative balance between upwelling and downwelling varies from year to year.

During a vessel-based scuba diving expedition, “Huinay Fiordos 24” (HF24), focused on benthic fauna between Golfo Tres Montes (northern Golfo de Penas, 46°30'W) and Puerto Eden (49°S), dead baleen whales and skeletal remains were discovered south of Golfo de Penas and at Golfo Tres Montes. Here we describe by far the largest ever recorded MME of baleen whales at one time and place. Our analyses focus on the location and cause of the mortality.

MATERIALS AND METHODS

Field surveys
The vessel-based HF24 scuba diving expedition, from April 15 to May 8, 2015, aimed to inventory the benthic fauna of the area between Golfo Tres Montes (northern Golfo de Penas, 46°30'W) and Puerto Edén (49°S). By chance, VH and her team discovered recently dead baleen whales and skeletal remains in and close to the entrance of the 14 km long Estero Slight and in the Canal Castillo situated 235 km to the south (Figs. 1, 3, Table 2). Georeferences and photographs of different views were taken, whales measured, and species and sex identified whenever possible. Between May 25 and 31, the Chilean Fisheries Service (SERNAPESCA), with the support of the Chilean Navy (Armada) and the Criminal Investigation Department of the Civil Police (PDI), organized a vessel-based trip to the location of the dead whales in Estero Slight to investigate possible anthropogenic reasons behind the mortality. During this trip, genetic samples for species identification were taken, one ear bone was extracted and stomach and intestine contents of two whales were tested for presence of PST and AST (Fiscalía de Aysén, 2015). During a subsequent aerial survey on-board a high wing airplane Cessna 206, between June 23 and 27, 2015, CSG, VH and FH surveyed the coasts along the shores of Golfo de Penas. This aerial survey covered the coastal area between the Jungfrauen Islands (48°S) and Seno Newman (46°39'S) from altitudes between 100m and 850m and at speeds between 100km/h and 200km/h (Figs. 1, 4, Table 2). Due to limited flying time (unstable weather conditions and the inability to refuel in the area) data collection was focused on counting whale carcasses, recording GPS positions and taking photographs. A GoPro camera filmed continuously until reaching Seno Newman. The researchers on the flight counted carcasses and marked their coordinates while an audio recorder captured the carcass number, position, orientation, photo number, photographer and geomorphology of the beach. Whale counts were repeated in all areas except Seno Newman due to adverse weather conditions. Since there are no
landing opportunities in this remote and unpopulated area it was not possible to take samples or
close-up photos, or to search for additional whale bones.

In addition to the whale carcasses and skeletons from the two surveys, some whale
carcasses and skulls were reported between February and June 2015 by boat crews navigating
the west coast of Taitao Peninsula and the coast between 49°15' and 51°S (Table 2). Between
January 23 and March 1, 2016 (Expedition Huinay Fiordos 27) and between April 27 and May
30, 2016 (Expedition Huinay Fiordos 29), two additional vessel-based expeditions were carried
out, each to Seno Escondido, Seno Newman and Estero Slight, with the aim of searching for
new carcasses, taking samples for genetic and red tide analyses, and performing oceanographic
transects. Data from those surveys are included here, but most of the analyses of the samples
will be published in a separate paper.

Samples of marine invertebrates were collected under permit of Subsecretaria de Pesca y
Acuicultura (R.EX. 1295 del 27.04.2016). Samples of cetacean carcasses were authorized by
SERNAPESCA, Region de Aysen (Acta Numbers 2016-11-10 and 12).

**Satellite image**
A high resolution satellite image was taken of Seno Newman on August 13, 2015 using the Pleiades-1 Satellite. The 16-Bit ortho-rectified GeoTIFF Multispectral (R-G-B-NIR) and Panchromatic files have been analyzed to count whale carcasses and determine their geographic positions (Fig. 5). The whales identified in the satellite image were compared to the photos and GPS locations obtained during the overflight, and cross matched with reference to nearby geomorphological features.

**Taxonomic analysis**

Whales were identified in situ during the vessel-based expedition based on morphological characteristics. The species identification of the specimens from which tissue was sampled during the SERNAPEsca expedition to Estero Slight was confirmed genetically by MJP (Fiscalía de Aysen, 2015). A 675 bp fragment of mitochondrial DNA control region was amplified using the primers using the primers M13 Dlp1.5 5’-TGTAAAACGACAGCCAGTTCACCCAAAGCTGRARTTCTA-3’ and 8G 5’-GGAGTACTATGTCCTGTAACCA (Dalebout et al. 2005) and sequenced in both directions.

Amplification reactions were performed in a total volume of 25 µl with 5 µl PCR buffer 10X, 2 µl MgCl2 50 mM, 1 µl of each primer, 2 µl dNTP 200 mM and 0.3 µl Taq DNA polymerase (Invitrogen Life Technologies) and 50 ng DNA. The PCR temperature profile was as follows: a preliminary denaturing period of 2 min at 94 ºC followed by 30 cycles of denaturation for 30 s at 94 ºC, primer annealing for 40 s at 56 ºC and polymerase extension for 40 s at 72 ºC. A final extension period for 10 min at 72 ºC was included.

**Taphonomy**
Analysis was carried out, following biostratinomic criteria, on different subsets of the whale remains recorded during the overflight and the vessel-based surveys. Characterization of the depositional state of the carcasses was based on a post hoc analysis of the assemblage, exclusively through photographs, classifying the carcasses into three taphonomic classes according to previous studies of biostratinomic processes in marine mammals (Pyenson et al., 2014, Liebig et al., 2003, 2007, Schäfer, 1972). The aspects considered were: anatomic position of the carcasses (ventral, dorsal or lateral side up; n=201), deposition site (rocky or sandy, n=295), and the disarticulation and degree of decay of the carcasses. These final two aspects were sorted into classes to estimate the sequence of disarticulation/decay addressing two aspects: time since death (n=245) and drift time/distance of the carcass (as a proxy to estimate the relative location of death, n=151).

To assess the time since death, three categories were defined, reflecting a straightforward order from the least decomposed to the most disarticulated carcass/skeleton. “Class 1” refers to carcasses in the lowest to relatively medium state of decomposition for these assemblages. Included in this category are complete carcasses with skin, complete carcasses without skin, and complete carcasses with partially exposed bones (see Fig. 6A). “Class 2” includes carcasses in a relatively greater state of decomposition but still maintaining their longitudinal axis, although some bones may be scattered (see Fig. 6B). Finally, “Class 3” refers to isolated skeletal remains with no soft tissue, such as skulls, dentaries or postcranial remains (see Fig. 6C). Thus, the sequence of “time since death” should reflect ranges from less than 3 months (Class 1), several months, but probably less than 6 months (Class 2), to a year or more (Class 3).
The analysis of the location of death, namely whether the carcasses are para-autochthonous or allochthonous, was addressed by evaluation of the time that the carcasses had remained floating in the water column and at the surface (see Schäfer, 1972). For this, we defined two classes, depending of the presence or absence of the skull, as a proxy for the time floating and the potential distance between the site of mortality and the observed site of deposition (Fig. 7) (Toots, 1965; Voorhies, 1969; Behrensmeyer 1973; Holz and Simoes, 2002; Liebig, 2003). Thus, “Class A” includes carcasses that preserve the skull and “Class B” includes those without a skull. For this analysis we excluded skeletons which were considered older than a year (minimum age, based on field observations of AVT from 2016 expedition to the site of the mortality).

A geomorphological analysis was made using photographs and Google Earth (Terrametrics, 2015). We classified the type of depositional locality (i.e. sand/pebble dominated beach or rocky outcrop) (Table 2) in order to assess the relationship between these aspects and the taphonomic categories mentioned above; for instance, whether carcasses that had been transported further and disarticulated (allochthonous) were more prevalent at high energy sites (i.e. rocky outcrops) and articulated (para-autochthonous) carcasses more prevalent in low energy environments (i.e. sandy beaches).
To compare the density of the death assemblages at Golfo de Penas with known extinct and extant death assemblages recorded in the literature, we measured linear dimensions of the geomorphological units (i.e. length and width of the beach), through the measure tool in Google Earth, using the highest resolution satellite images available, at sites where assemblages were found. In this manner, the geographic areas corresponding to the death assemblages were calculated and the density determined by dividing the number of specimens in each assemblage by its area.

Analysis of the petrotympanic complex (ear bone)

CSG studied the bones of the middle and inner ear of one whale, collected during the SERNAPESCA expedition. A volumetric computed tomography in the Morita tomograph (box of 60 mm, 500 cuts) was carried out. The images were visualized with Osirix Dicom viewer v 5.6 32-bit in search for fractures or micro-fractures, which would appear as black gaps in the bony tissue.

Analysis for toxins (PST/AST)
Bivalve tissue was sampled in Estero Slight on April 22 and on May 25, 2015 (2 samples in total), and in Estero Slight, Seno Newman and Seno Escondido between January 23 and March 1, and April 27 and May 30, 2016 (22 samples in total). The stomach content and intestine content of two whales from Estero Slight were sampled on May 25, 2015. On February, 2016, one sample of duodenum content was obtained from a freshly dead whale observed in Estero Slight. At the same period, one sample of surface-swimming *Munida* spp. was collected at 46° 29.730'S, 74°55.722'W. All samples were analyzed *in situ* for presence of PST using the protocol already described for the shellfish tissue and stomach content samples. Samples from 2015 were analyzed by DC, while the samples from 2016 were analysed by KMC. The tissue was homogenized using a blender and mixed in a 1:1 ratio with a field extraction fluid composed of 2.5 parts of rubbing alcohol (70%) to one part white vinegar. The mixture was then homogenized manually and filtered through a paper filter (paper filter #4). The extract obtained after filtration was then used to detect the presence of toxins through rapid field test kits from Scotia Rapid Testing for PST and AST. For this, 100 μl of the extract was placed in a test tube containing running buffer, mixed and then 100 μl of this mixture was placed in a lateral flow ELISA (enzyme-linked immunosorbent assay) test strip with antibodies specific for PST (saxitoxin and its derivative toxins) and AST (domoic acid). These tests were left to develop for 1 hour before the results were read.
Twenty-two phytoplankton samples were collected in Estero Slight, Seno Newman and Seno Escondido between January 23 and March 1, and April 27 and May 30, 2016, using a 20 μm mesh size plankton net in a vertical tow from 15 m depth. The phytoplankton present in these samples was concentrated using the net, and a 100 μl subsample was placed in a tube with 0.1 M acetic acid and mixed. 100 μl of this mixture were then added to a test tube containing running buffer and an aliquot of this mixture of the same volume was placed in a ELISA test strip for PST and left to develop for one hour before results were read.

These qualitative PST test strips are extremely sensitive due to the local toxin profile, which is high in GTX2/3, resulting in detection limits below 32 μg STX Eq/100 g of tissue. The detection limit for the AST tests was reduced to 2 ppm of domoic acid by modifying the standard sample preparation protocol by eliminating the dilution of the sample before mixing it with the buffer.

A graphical analysis of the geographic and temporal distribution of PSP events, presence of harmful microalgae and environmental variables in the affected region (43°S-51°S) from 2007 to July 2015 and from March 2016 was performed with the data obtained from the red tide monitoring program conducted by the SERNAPESCA (RS Galdames RS, personal communication, 2015), in which mytilid samples are analyzed at several stations throughout Chilean Patagonia approximately once a month by the “Laboratorios SEREMI Salud”, from Aysén and Magallanes regions at southern Chile.

**Drift model**
Floating objects are directly affected by surface currents, wind and waves. Wind both drives the Ekman drift of surface water (Ardhuin et al., 2009) and exerts a direct drag on the emerged surface of an object (Breivik et al., 2012). Stokes drift, the net forward transport due to non-closed particle trajectories resulting from passing waves, also contributes to the transport of floating objects. The drift of whale carcasses was simulated by parametrising the contribution of these components, based on objects of a similar size from search and rescue models (Breivik et al., 2012; Peltier et al., 2012). Due to the large uncertainty in carcass drift characteristics, parameters were varied stochastically within a wide range of possible values.

Use was made of existing current and wave products, the HYCOM daily 1/12 simulation (Wallcraft et al., 2009), and waves from ECMWF ERA-Interim reanalysis (Dee et al., 2011). Winds were taken from a custom downscaling of NCEP NFL boundary conditions using the WRF model (Skamarock et al., 2008) to a sub-4 km grid size. Drift scenarios were run by stepping forward in time from hypothetical sites and times of mortality. All of these sites were in shallow water, since carcasses resulting from mortality in deep water have a tendency to sink and not resurface (Smith et al., 2015). A horizontal diffusion coefficient of 10 m²s⁻¹ was included in drift tracks to represent unresolved physical processes. While the resolution of the current and wave datasets is inadequate to represent detailed coastline or seabed geometry, or the interior of the fjords, the drift model does clarify the expected distribution and spread of carcasses from localized sources.

Large scale wind stress
The large-scale tendency toward upwelling or downwelling provides a key driver of coastal ecosystems. This was assessed using ECMWF ERA-Interim reanalysis data (Dee et al., 2011). It is the alongshore component of wind stress that drives Ekman transport normal to the coast and consequent upwelling or downwelling. Since upwelling and downwelling are cumulative processes, a time-integrated wind stress was calculated (e.g. Pierce et al., 2006) from a base time of the vernal equinox (September 21). Stress was estimated from reanalysis winds at 10 m elevation according to Large and Pond (1981). The large scale change in coastal orientation was taken into account in extracting the alongshore wind component, although localized inlets, bays (including the Golfo de Penas) and islands were not considered.

RESULTS

Field surveys and toxicity tests

Of the total of dead whales observed in all expeditions and reports in 2015 (367), 35 recently dead whales and 12 skeletal remains were discovered during the HF24 expedition: 31 carcasses and 12 skeletal remains were found in and close to the entrance of the 14 km long Estero Slight and four carcasses in Canal Castillo, situated 235 km to the south, as well as many whale bones on different beaches (Fig. 3, Table 2). Three-hundred and five carcasses were mapped during the overflight between the Jungfrauen Islands (~48ºS) and Seno Newman (46º39'S). In addition to this total of 284 whale carcasses and 21 skeletons from the two surveys, 51 whale carcasses and 11 whale skulls were reported between February and June 2015 by boat crews navigating the west coast of Taitao Peninsula and the coast between 49º15’ and 51ºS (Table 2, Fig. 4).
On some photos what could have been carcasses of smaller animals (possibly dolphins and/or sea lions) were seen, but due the flying altitude, speed and weather conditions, the photo quality and resolution did not allow their conclusive identification as actual carcasses. In Estero Slight, one dead pinniped was found on the shore from the vessel. During the SERNAPECSA expedition one Otariidae skull was found and photographed in the same channel but the correspondence of the carcass and the skull could not be established.

The 28 whale carcasses that could be identified unambiguously to species level were all sei whales (*Balaenoptera borealis*); 15 of these identifications were confirmed genetically. Seven specimens could be identified as males and ten as females. One hundred and twenty-nine carcasses were identified as baleen whales of the Balaenopteridae family or rorquals. The 30 whales examined in detail in Estero Slight during the vessel-based expedition were between 6 m and 15 m long, hence included both juvenile and fully grown specimens.

None of the examined whales showed any evidence of disease or traumatic damage. The anatomic structures of the ear bone were in good condition showing no damage; the stapes were articulated in place, and the bony tissue showed no fractures (Fig. 8). The analysis of locally collected mytilids in April and May 2015 and of the stomach and intestine content of two whales in May 2015 showed presence of PST and AST.
In 2016, 16 fresh carcasses were observed during the HF27 and HF29 vessel-based expeditions to Golfo Tres Montes; five further were reported by boat crews navigating the southern part of Chilean Patagonia. None of the examined whales showed any evidence of disease or traumatic damage. Thirty-six rapid tests on PST were run using mussels (12 tests), *Munida* (2 tests), and phytoplankton (22 tests) in Seno Escondido, Seno Newman and Estero Slight. Most of the samples collected during the 2016 expeditions proved to be negative for the presence of PST, nevertheless, both expeditions detected the presence of PSP in the phytoplankton collected at the entrance of Seno Newman. A sample collected at the head of Seno Newman was negative for PST, indicating that the toxic phytoplankton was preferentially located at the mouth of this inlet and nearby areas of the Canal Chaicayán.

**Biostratinomic analysis**

Of the 367 dead whales observed in 2015, 305 carcasses were mapped between Seno Newman (46º39'S) and Jungfrauen Islands (~48ºS). Those carcasses could be grouped into five assemblages (Figs. 1, 9, Table 2), defined as a group of carcasses in close proximity. The assemblages were called Golfo de Penas, Jungfrauen Islands, Seno Escondido, Seno Newman and Estero Slight.

Some carcasses were floating (11), but most (284) were deposited ashore (Figs. 3 to 5). In general, they were tide-oriented (parallel to the coast line) and all of the classified carcasses from the overflight were lying on their back or side (ventral up, 44.3%; lateral up, 55.7%) (Table 3, Fig. 11C), while only one specimen (from HF24) was found in a dorsal up position (data not included in analysis due to different time of observation).
With respect to the classification of “time since death”, 68.8% of the carcasses were classified in class 1 (less than 3 months), 24.9% in class 2 (less than 6 months) and 6.3% in class 3 (more than a year) (Fig. 11A-B, Table 4). With respect to “time at sea”, 147 (87%) of the carcasses were classified in class A (short time/distance of drift), while only four (13%) were identified as class B (long time/distance of drift) (Fig. 11 C, Table 4). There was no pattern relating the geomorphological unit (sandy: 34%, pebble: 27%, rocky beach: 34%) to the taphonomic classes.

The carcasses found in April in Estero Slight were classified in stage 2 of Geraci and Lounsbury (2005) indicating a few days to weeks since death; this would be classified as class 1 in the taphonomic classes of the present study.

The density of whale carcasses was in average 1050/km², considering all assemblages recognized (Table 5).

**Carcass drift and potential source locations**
The distribution of beached carcasses was simulated from four illustrative source locations (Fig. 12A-D). In each case, calculations tracked 13000 hypothetical carcasses, reflecting source times spanning a 2-month period from mid-February to mid-April 2015 and a range of drift model parameters. The spread of stranding locations therefore represents variability of the current, wind and wave environment during this period as well as the uncertainty in model parameters and a diffusive component to the drift tracks. While each of the illustrated source locations leads to strandings distributed over several hundred kilometres of coastline, there are important differences in these distributions. A simulated source in Golfo Tres Montes (northern Golfo de Penas) leads to strandings throughout the Golfo de Penas (Fig. 12A), including in the Golfo Tres Montes itself. No other source location (Fig. 12B-D) leads to strandings in Golfo Tres Montes due to the direction of prevailing currents and the sheltering effect of Peninsula Taitao. Similarly, only a source to the north of Peninsula Taitao leads to strandings in that region (Fig. 12B). Carcasses originating in the Golfo de Penas have a tendency to be transported to the south by prevailing currents (Fig. 12A, C, D).

Inter-annual variation in upwelling or downwelling
Comparison between the cumulative alongshore wind stress for the year in question and the previous 20 years (Fig. 13) reveals that the months immediately prior to the mortality event were anomalous. North of the study area, at 45°S, there was an anomalously strong tendency toward upwelling (an upward trend in Fig. 13), making this one of the most upwelled years of the period. At the latitude of Golfo de Penas and further south there was a net tendency to downwelling (a downward trend in Fig. 13), but punctuated by upwelling events, making this one of the least downwelled years of the period.

**DISCUSSION**

Possible causes of death (Table 6) need to be analysed for a mechanism that is capable of synchronous killing of hundreds of whales, apparently all or most of the same species (with few exceptions, i.e. one confirmed pinniped). Baleen whales, in contrast to odontocetes, are less social and do not use echolocation to navigate (Perrin et al., 2009b). The latter characteristics are key aspects used to explain mass mortalities in odontocetes.

Possible causes for the death of hundreds of baleen whales include a lethal and highly contagious unknown virus or infection, noise-related mechanisms at sea, and intoxication by biotoxins (domic acid, saxitocin, etc; Geraci et al., 1989; Fire et al., 2010; Lefebvre et al., 2016; Pyenson et al. 2014, Table 6). In this assemblage the individuals could not be tested for viruses or bacteria, due to their advanced state of decomposition. There was no evidence of pathological modifications that could be attributed to such a cause, however, it is not possible to completely discard this hypothesis.
The only potentially lethal noise-related mechanism for a baleen whale are very intense noises associated with blasting in close proximity (Ketten 1992). This could injure the animal and cause haemorrhage or provoke panic, disorientation and favour entrapment (not yet described for baleen whales, Goldbogen et al. 2013). Although there was no evidence of bony damage or micro-fracture of the one examined periotic, this cannot be excluded for the other individuals. Any other noise-related damage could neither be ruled out due to the decomposition of the soft tissue structures, nevertheless there is no evidence that for baleen sonar and ground noise could trigger more than non-lethal behavioural and temporary effects (Goldbogen et al. 2013). The strongest argument against this hypothesis is that whales died synchronously along hundreds of kilometres of shore line and at least five different sources of carcasses were identified (see discussion on drift models), which could only be explained by a large number of blastings along the coast during a very restricted time period. The study carried out by SERNAPESCA (Fiscalía de Aysén, 2015; Ulloa et al., 2016, available upon request from SERNAPESCA authorities) based on partial necropsies of two whales in late May 2015, found no evidence of any trauma or human interaction. The whales were already in decomposition stage 3 to 4 and class 1 of taphonomic classes used here.
Paralytic shellfish toxin (PST) is known to accumulate in the pelagic stage of the squat lobster *Munida gregaria* (MacKenzie & Harwood, 2014), an important prey of sei whales (Matthews, 1932). Older reports (Tabeta & Kanamura, 1970) and recent observations by boat crews (pers. comm. Keri-Lee Pashuk, 2015) indicate that squat lobster abundance fluctuates strongly and can reach extremely high concentrations, especially in Golfo Tres Montes (Tabeta & Kanamura, 1970). The presence of PST in mytilids from the area and in the whale carcasses and the absence of evidence for other causes of death leaves paralytic shellfish poisoning (PSP) as the most probable cause of death (Table 6). Although AST was also detected in one of the stomach content samples, it is not believed to be the cause of the MME as it was not detected by the toxin monitoring stations. A mixed assemblage of 40 skeletons from the Miocene in the north of Chile, dominated by rorqual whales and attributed to four recurrent HAB events, shows many similarities to the assemblages described here (Pyenson et al., 2014). The characteristics of the MME and the repetition in the same locality are common features for HAB-mediated mortalities (Brongersma-Sanders, 1957) (see Table 6, 7). MMEs through PSP in rorquals are thus not a recent phenomenon in the South East Pacific. Nevertheless, whale bone accumulations and reports of mortalities in Chilean Patagonia of up to 15 rorquals going back to at least 1977 suggest an increase in the frequency of mortalities (Table 8). Since the early 1990s HABs have been recorded every year in spring and autumn along the entire Patagonian coast but patterns are patchy and generally restricted to bays and fjords. The same is true the coast of the Northeast Pacific where HAB events have been increasing in strength and extension (Cook et al., 2015). This MME coincided with increased mortality of baleen whales along the west coast of North America in 2015 (NOAA, 2015b), and with the most extended and longest lasting HAB event registered there (NOAA, 2015c). A positive correlation between the occurrence of PST
b Blooms and the ENSO indices in northern and central Patagonia has been shown (Cassis et al., 2002; Guzmán & Pizarro, 2014). A similar correlation between the abundance of toxic harmful algae and surface temperatures, which in turn are affected by ENSO, was observed in Aysén by Cassis et al., (2002). El Niño events have increased in frequency and strength due to global warming (Cai et al., 2014). A strong El Niño event began to build in September 2014, which became the strongest El Niño of all time (NOAA, 2015a). The calculated cumulative windstress (Fig. 13) suggests that during this period there was an anomalous tendency towards coastal upwelling and associated nutrient delivery. Exceptionally high levels of PST, ten times higher than usual peaks, were reported in March 2015 from the closest monitoring site 120km north of the mortality area (Isla Canquenes, Fig. 14).

The presence of PST during February 2016 was accompanied by deep red/brown surface water discoloration due to the high abundance of *Alexandrium catenella*. This harmful algal bloom was coincidental with an unusually large bloom of the same toxic species in the waters around Chiloé island (42°S) (Hernández et al, 2016). The May 2016 expedition did not observe water discoloration at this location, nevertheless the phytoplankton samples obtained at the mouth of Seno Newman were also positive for PST, indicating that this toxic species can be present in the area for long periods of time during the summer. The PST levels at Isla Canquenes were not elevated in 2016; however, at two sites in the Messier Channel levels four and seven times higher than usual peaks, were measured (Fig. 15).
Rorqual whales sink shortly after death (Smith et al., 2015). Once carcasses have sunk below a depth of 50 m to 100 m, they tend not to re-float since hydrostatic pressure compresses decomposition gases (Smith et al., 2015). The bathymetry in the Golfo de Penas area and off the steeply sloping Taitao Peninsula (Fig. 12) requires that the whales that washed ashore all died near the shore. Thus, we conclude that despite common belief (Perrin et al., 2009a) sei whales opportunistically feed close to shore and may even follow their prey into narrow and shallow inlets and channels. This hypothesis is supported by the fact that live Sei whales were observed nearshore in Golfo de Penas and Estero Slight on several occasions (Table 8).
The drift model suggests that the observed carcasses originated from multiple sites. The carcasses found in the two fjordic inlets of Seno Newman and Estero Slight (62% of the total) probably died not far from where they stranded, either in the Golfo Tres Montes or within the inlets themselves (Figs. 1, 9), since source locations elsewhere in Golfo de Penas or north of Taitao Peninsula do not lead to carcasses in this region (Fig. 12B-D). Although the inlets themselves are not resolved in the drift model, the net seaward surface outflow of a fjord would only allow carcasses to collect toward its head (as observed) if wind and waves in that direction dominated their drift, or if they died close to the site where they were found. Modeled winds were occasionally toward the head of Seno Newman, on March 20 and during April 14-18, but almost never in the case of Estero Slight (Fig. 16), so it is highly likely that the carcasses found within these inlets were the result of mortality within the inlets themselves. Carcasses from within these inlets could, however, be exported to nearby coastal waters and then distributed around Golfo de Penas as seen in the drift simulations for a source in Golfo Tres Montes (Fig. 12A), so mortality within the inlets of Seno Newman and Estero Slight could have been the source for carcasses found elsewhere in Golfo Tres Montes or Golfo de Penas.

The accumulation of carcasses in the convoluted and extremely shallow Estero Escondido is similarly unresolvable by the drift model, but it also appears highly likely that these carcasses resulted from mortality within the inlet itself. It is however unclear why dozens of large whales would swim into a narrow inlet which in most parts is only between 2 and 7 m deep (maximum depth 15 m just inside extremely shallow entrance) (Fig. 17).
Drift predictions from sources within Golfo de Penas, or to the south (Fig. 12A, C-D), never led to carcasses on or to the north of Taitao Peninsula, therefore the observed carcasses on the exposed shoreline in that region (Estero Cono) likely originated close to shore, either locally or to the north. The carcasses found between the southern end of Golfo de Penas and 49°S either died very close to where they washed ashore or were transported from the large concentrations in Golfo de Penas by clockwise flow within the gulf. The five whales between 49°S and 51°S probably died locally.

Surveys in the Golfo de Penas area have sighted sei whales in all seasons, with up to 600 individuals, some even near to the shore of Golfo de Penas and Estero Slight (Table 8). Therefore, the number of whales that have been exposed to toxins could be considerable. It has been calculated that less than 10% of the gray whales that are estimated to die each year in the eastern North Pacific are washed ashore, while most sink and do not resurface (Rugh et al., 1999). Assuming a similar ratio, our observations may greatly underestimate the actual magnitude of this mortality event. Many whales may have sunk and never re-surfaced, and a significant number of carcasses may have been washed ashore on the many remote beaches that could not be surveyed due to adverse weather conditions. Others may have been destroyed by wave action from winter storms on the high-energy rocky shores that dominate the area.

In other reported MMEs, the period of the time of a massive mortality was determined by considering the number of carcasses, and their temporal and spatial extent. This ranged from two years (gray whales; Gulland et al., 2005) to a few weeks (Humpback whales of cape Code; Geraci, 1989). To determine the time span of this MME, the classification of carcasses was carried out following the disarticulation sequence proposed by Schäfer (1972).
Time since death and time of transportation at sea of the carcass are slightly different in terms of articulation and state of decomposition. Following Schäfer (1972), the first breakage of the outer tissue of a carcass at sea should occur within a week to a month, although in Chilean Patagonia the time span could be a little greater due to the low temperature. In addition, some carcasses could have drifted for some weeks, arrived intact on shore, and then decayed more rapidly exposing the bones, while other carcasses could have floated longer until skull, tail and limbs were disarticulated, but decayed more slowly due to the colder water temperatures. This was in agreement with the comparisons of the disarticulation of carcasses in the field assessed through the photographs of the different expeditions to the same area (Estero Slight, in April and May 2015). Nevertheless, at the present assemblage, the time until the bones were exposed was extended from 1 to around 3 months (class 1) and time of disarticulation was shifted from 3 to 6 months (class 2), due to the low average temperature in the study area.
Considering available information on MMEs time scales, it is reasonable to suppose this event occurred over a time span of approximately three to maximum six months (November 2014 to April 2015). Nevertheless, the record of other crews (Table 2) and modeled oceanographic conditions (see “Carcass drift and potential source locations”, above) point to the beginning of the die off around February at Golfo de Penas. Thus the class 2 carcasses would indicate another pulse of corpses arriving at the same area in a different taphonomic condition, which could suggest: a) longer drift time/distance transport; b) equal arrival but different time of death; or c) higher energy environment. The classification of “time at sea” analysis suggested that drift time was in its majority the same with a similar proportion of class a (short drift time/distance). The analysis of the anatomic positions suggests the allochthonous nature of the deposits in all assemblages (see Pyenson et al., 2014). Only two carcasses were found in a dorsal up position which suggests live stranding.

The average density of Golfo Tres Montes assemblages is equivalent to one third of the density calculated for Cerro Ballena, a Late Miocene (~9 m.y.a.) fossil red tide linked assemblage of northern Chile (3000/km², Pyenson et al., 2014) (Table 5). However, this difference is likely to have a sampling bias since in Golfo Tres Montes and Golfo de Penas we could only could the carcasses along the coastline, but not on the seafloor.

CONCLUSIONS
1. The whales died at sea, close to where they beached. About 90% of the whales died during one MME (94.7% for time since death and 87% for time at sea analysis), most probably between February and April 2015. No major mortality has occurred in the same area in 2016, but mortalities in other areas cannot be excluded (see Fig. 15 for 2016 toxin levels).

2. Since it is likely that all or most of the affected whales were sei whales, the documented mortality may represent a significant increase over the usual death rate of Southern Hemisphere sei whales (Reilly et al., 2008). If the frequency and magnitude of MMEs increase due to climate change this would have a significant impact on the local population and threaten the recovery of this endangered species, which in the Southern Hemisphere was reduced by whaling from about 100,000 to 24,000 individuals by 1980 (Perrin et al., 2009a).

3. This MME and historical data suggest that, at least during years with abundant squat lobsters, the Golfo de Penas is one of the most important feeding grounds for sei whales, hosting the largest and densest known sei whale aggregations outside the polar regions.

4. Discoveries of dead whales in this remote area are chance finds. To clarify the extent, frequency and magnitude of MMEs, an assessment and systematic monitoring of whale populations in Central Chilean Patagonia is necessary. We suggest to do this through regular satellite images.
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Figure and table captions

Fig. 1: Location of dead whales and skulls found in Chilean Patagonian. Boat track: green (HF24), flight track: blue (HF25) A) Golfo de Penas, B) Golfo Tres Montes, C) Seno Escondido.
Fig. 2: Satellite image (MODIS Aqua) showing the concentration of chlorophyll a on March 23rd, 2015. Areas where most whales were found are circled.
Fig. 3: Documented whale carcasses and skeletal remains during a vessel survey in April 21st 2015 in Caleta Buena, Estero Slight. A) and B) skeletal remains C) Recently dead sei whale. Photos: Keri-Lee Pashuk, all rights reserved.
Fig. 4: Documented whale carcasses and skeletal remains during an overflight on June 25st 2015, Seno Escondido.

The numbers correspond to the whale identification numbers in Table 1. Photos: Vreni Häussermann, all rights reserved.
Fig. 5: A. A. Satellite image on August 13th 2015, used to count the carcasses along Seno Newman. B-C-D. Detail of the carcasses highlighted in A.
Fig. 6: Biostratinomic classification addressing the decomposition/desarticulation of carcasses/skeletal remains assessing to the time since death. A-B) Class 1, carcasses in the lowest to relatively medium state of decomposition, C-D) Class 2, carcasses in a relatively greater state of decomposition, but still maintaining their longitudinal axis, although some bones may be scattered, E-F) Class 3, isolated skeletal remains with no soft tissue.
Fig 7: Biostratonomic classification of the location of death of carcasses/skeletal remains

A) Carcasses preserving the skull, B) Carcasses lacking the skull.
Fig. 8: Digital images obtained through computed volumetric tomography (CVT) scanned at Morita Tomography (box of 60 mm, 500 slices). All acoustic anatomical structures of the middle ear (ossicles: stapes), internal ear (cochlea: spiral lamina) and the semicircular canals are seen in perfect condition.
Fig. 9: Maps showing the five assemblages of whale carcasses. (A) Golfo de Penas, (B) Seno Escondido, (C) Seno Newman, (D) Estero Slight, (E) Jungfrauen Islands. State of decomposition color-coded: Yellow (state 1; least decomposed, all articulated), orange (state 2, intermediate decomposed), red (state 3; isolated remains).
**Fig. 10**: Inflation of the tongue and its implication for whale carcass deposition. The greater proportion of carcasses deposited in a lateral position and to a lesser extent in the ventral-up position reflects the hydrodynamics of the body in the sea as determined by the inflation of the abdominal region (9) and mainly of their tongues. A) Inflated tongue in a very recently dead sei whale (weeks) indicated by the arrow head. B) Close-up of the mouth with dislocate mandibles due to the previous inflation of the tongue (arrow head), which is decayed and removed by scavengers. C) Whale carcass seen from the overflight deposited in lateral position and its protuberant inflated tongue (arrow head).
**Fig. 11**: Graphs showing the proportion of the total classified carcasses in the biostratonomic analysis. A) Time since death, B) Time since death, combining Class 1 and 2, C) location of death, D) Anatomical positions of carcasses (lateral, ventral and dorsal-up).
Fig. 12: Location of beached carcasses (blue) predicted by the drift model from four possible mortality locations (red stars). Mortalities during a 2-month period are simulated, from mid February to mid April 2015, with multiple carcasses (n=200) of varying drift properties released each day to predict the range of resulting carcass locations. Green vectors show time-averaged surface currents for this period (HYCOM model). Depth contours at 50 m and 100 m are indicated (GEBCO), although nearshore waters and inlets are not resolved.
**Fig. 13:** Cumulative alongshore component of near-shore wind stress (red) from ECMWF ERA-Interim reanalysis winds at three latitudes, with an origin time of the vernal equinox, September 21, 2014. Gray shading shows the envelope of variability experienced during 1995–2014, with darker shading indicating one standard deviation from the mean for this period. Vertical lines show the timing of vessel (green) and aerial (blue) observations of whale carcasses.
Fig. 14: Spatial distribution of PST (STX. Eq./100g tissue) as measured in mytilids and the relative abundance of *Alexandrium catenella* between 43°S and 51°S in March 2015. Insert shows the toxin level at the closest site to the Golfo de Penas, Isla Canquenes (45°43′31″S; 74°06′51″W) measured between March 2010 and March 2015. Shellfish consumption is unsafe for humans if values rise above 80μg STX. Eq./100g tissue.
Fig. 15: Spatial distribution of PST (STX. Eq./100g tissue) as measured in mytilids between 43°S and 51°S in March 2016. In 2016, the PST levels in the Golfo Tres Montes region were not elevated. However, values four to seven times higher than usual peaks were measured in the channels of Central Patagonia. Shellfish consumption is unsafe for humans if values rise above 80μg STX. Eq./100g tissue.
**Fig. 16:** Wind roses at the entrance to two inlets, Seno Newman (A) and Estero Slight (B), derived from a local high-resolution implementation of the WRF model. Spoke lengths indicate the frequency of occurrence of winds from each direction. Colors represent speed. Seno Newman has a significant up-inlet component (winds from SSW) but Estero Slight does not (winds from NNE).
Fig. 17: Nautical maps of Escondido and Slight Inlet. A) Section of the Bahia San Quintin showing Escondido Inlet (maximum depth 15m). B) Section of Hoppner Bay showing Estero Slight (maximum depth 152m). Sources: Map nr 8820 and 8810 from armada de Chile. Newman Inlet is poorly charted with only five depths indicated along the inlet, the largest being 82m.
**Table 1:** Recorded mass mortality events of baleen whales (updated from Table 1 in Rowntree et al. (2013))

<table>
<thead>
<tr>
<th>Region/site</th>
<th>Time span</th>
<th>Species</th>
<th>Number</th>
<th>Age classes</th>
<th>Cause of death</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cape Cod (USA)</td>
<td>5 weeks (11/1987)</td>
<td>humpback</td>
<td>14</td>
<td></td>
<td>HAB (saxitoxin)</td>
<td>Geraci et al., 1989</td>
</tr>
<tr>
<td>Eastern North East Pacific</td>
<td>throughout 1999</td>
<td>gray</td>
<td>283²</td>
<td>mostly adults</td>
<td>malnutrition?</td>
<td>Gulland et al., 2005</td>
</tr>
<tr>
<td>Eastern North East Pacific</td>
<td>throughout 2000</td>
<td>gray</td>
<td>368</td>
<td>mostly adults</td>
<td>malnutrition?</td>
<td>Gulland et al., 2005</td>
</tr>
<tr>
<td>Upper Gulf of California (Mexico)</td>
<td>? (2009)</td>
<td>unknown</td>
<td>10</td>
<td>unknown</td>
<td>Rowntree et al., 2013</td>
<td></td>
</tr>
<tr>
<td>Australia</td>
<td>throughout 2009</td>
<td>humpback</td>
<td>46</td>
<td>mostly calves and juveniles</td>
<td>unknown</td>
<td>Coughran et al., 2013</td>
</tr>
<tr>
<td>Brazil</td>
<td>throughout 2010</td>
<td>humpback</td>
<td>96</td>
<td>mostly calves and juveniles</td>
<td>unknown</td>
<td>Rowntree et al., 2013</td>
</tr>
<tr>
<td>Peninsula Valdés (Argentina)</td>
<td>2005-2011¹</td>
<td>southern right</td>
<td>420</td>
<td>mostly calves</td>
<td>unknown (HAB-related?, starvation?, kelp gull harassment?)</td>
<td>D'Agostino et al., 2015; Wilson, 2015</td>
</tr>
<tr>
<td>Puerto Edén area (Chile)</td>
<td>March 2011</td>
<td>sei and/or minke</td>
<td>3</td>
<td>unknown</td>
<td>this paper</td>
<td></td>
</tr>
<tr>
<td>Estero Cono (Chile)</td>
<td>March 2012</td>
<td>sei and/or minke</td>
<td>15</td>
<td>unknown</td>
<td>Pers. comm. Fischer RM, 2015</td>
<td></td>
</tr>
<tr>
<td>Puerto Edén area (Chile)</td>
<td>January 2014</td>
<td>sei and/or minke</td>
<td>5</td>
<td>unknown</td>
<td>Pers. comm. Cristie C, 2015</td>
<td></td>
</tr>
<tr>
<td>Between 46° and 51°S, mainly Golfo de Penas (Chile)</td>
<td>February to early April 2015²</td>
<td>probably all sei</td>
<td>305</td>
<td>all</td>
<td>HAB</td>
<td>this paper</td>
</tr>
<tr>
<td>Alaska/British Columbia (USA/Canada)</td>
<td>Mai/June 2015</td>
<td>fin, humpback, grey</td>
<td>38</td>
<td>unknown (HAB?)</td>
<td>NOAA, 2015b</td>
<td></td>
</tr>
</tbody>
</table>

¹ In total, 400 cetaceans died, including 8 baleen whales
² 106 in Mexico during 3 months
³ 116 died during 2012
⁴ 271 died within one month
### Table 3 – Proportion of carcasses in each anatomical position as recorded from the overflight survey and posterior photographic analysis.

<table>
<thead>
<tr>
<th>Anatomical position of Carcass</th>
<th>Unknown</th>
<th>Dorsal Up</th>
<th>Ventral Up</th>
<th>Lateral Up</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count</td>
<td>187</td>
<td>0</td>
<td>43</td>
<td>54</td>
<td>97</td>
</tr>
<tr>
<td>Proportion (%)</td>
<td>65.84%</td>
<td>0</td>
<td>15.14%</td>
<td>19.01%</td>
<td>100</td>
</tr>
<tr>
<td>Proportion (%) based on classified individuals only</td>
<td>-</td>
<td>0</td>
<td>44%</td>
<td>56%</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 4 – Minimal number of individuals (MNI) and proportion of carcasses in each of the classes of decomposition / disarticulation stages recorded at Golfo de Penas.

<table>
<thead>
<tr>
<th>Class</th>
<th>MNI</th>
<th>Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time since death</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>141</td>
<td>68.78</td>
</tr>
<tr>
<td>2</td>
<td>51</td>
<td>24.88</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>6.34</td>
</tr>
<tr>
<td>Total</td>
<td>205</td>
<td>100</td>
</tr>
<tr>
<td>Time at sea</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>147</td>
<td>97.35</td>
</tr>
<tr>
<td>B</td>
<td>4</td>
<td>2.64</td>
</tr>
<tr>
<td>Total</td>
<td>151</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5. Density of specimens in assemblages (specimens/km²).

<table>
<thead>
<tr>
<th>Assemblage 1 - Jungfrauen Group</th>
<th>Area (km²)</th>
<th>No. of specimens</th>
<th>Density (specimens/km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assemblage 2 - Escondido Inlet</td>
<td>0.02</td>
<td>47</td>
<td>1906</td>
</tr>
<tr>
<td>Assemblage 3 - Escondido Inlet</td>
<td>0.01</td>
<td>32</td>
<td>1987</td>
</tr>
<tr>
<td>Assemblage 4 - Newman Inlet</td>
<td>0.60</td>
<td>149</td>
<td>248</td>
</tr>
<tr>
<td>Assemblage 5 - Slight Inlet</td>
<td>0.04</td>
<td>40</td>
<td>952</td>
</tr>
<tr>
<td>Total area of assemblages/specimens</td>
<td>0.87</td>
<td>298</td>
<td>341</td>
</tr>
<tr>
<td>Average</td>
<td>0.17</td>
<td>59</td>
<td>1050</td>
</tr>
</tbody>
</table>
Table 6: Comparison of the usual causes of death with the evidence encountered at Golfo de Penas (GP).

<table>
<thead>
<tr>
<th>Cause of death for marine mammals</th>
<th>Main feature</th>
<th>Type of evidence (confirm.- discard)</th>
<th>Observation at Golfo de Penas</th>
<th>Expected in rorqual event</th>
<th>Oceanographic conditions near time of death</th>
<th>Rorqual Species recorded</th>
<th>References</th>
<th>Oceanographic Conditions Observed at GP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starvation by abundance surpassing carrying capacity</td>
<td>Thin blubber layer, or empty stomach, or numbers around 5% of population</td>
<td>Measurement, necropsy and population numbers nearby carrying capacity</td>
<td>Not likely, Sei whales are still recovering from whaling, last species to be hunted</td>
<td>Reported in one species</td>
<td>Low productivity event</td>
<td>Unknown. Reported in gray whales (Eschrichtius robustus).</td>
<td>Gulland et al. 2005</td>
<td>High productivity event</td>
</tr>
<tr>
<td>Military exercise with Sonar</td>
<td>Only confirmed in dolphins</td>
<td>ear damage and – or haemorrhage nearby the ears</td>
<td>Unknown</td>
<td>No military exercises public programed, chilean law for the protection of whales</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Goldbogen et al. 2013, Nowacek et al. 2007, Southall et al. 2007</td>
<td>Not reported</td>
</tr>
<tr>
<td>Trauma: Ship collision/entanglement</td>
<td>Evidence of trauma, small number (i.e. 8 deaths in 19 years in U.S.A.)</td>
<td>Lesions, hematoma,</td>
<td>No sign of internal or external lesion. Yes (small number of individuals at a time)</td>
<td>Not related.</td>
<td>Eubalaena glacialis</td>
<td>Kraus, 1990; Moore et al. 2004, Vanderlann y Taggart, 2007.</td>
<td>Not related.</td>
<td></td>
</tr>
<tr>
<td>Time since death</td>
<td>Condition of the carcasses</td>
<td>Age proportions</td>
<td>Sex proportions</td>
<td>Geographic position</td>
<td>Observed</td>
<td></td>
<td></td>
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<tr>
<td>Catastrophic – single event</td>
<td>Highly homogenous. Majority within one to a few classes (42)</td>
<td>Same as population rate</td>
<td>Same as population rate</td>
<td>Homogenous</td>
<td>Homogenous; see Tab. S2</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Time averaged</td>
<td>Highly heterogeneous. Several classes present.</td>
<td>Same as proportion of annual mortality of the population.</td>
<td>No pattern, different from ratio of population.</td>
<td>Heterogeneous</td>
<td>Homogenous; see Tab. S2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location of death</td>
<td>Condition of the carcasses</td>
<td>Anatomic position expected</td>
<td>Anatomic position expected</td>
<td>Orientation</td>
<td>Anatomic position observed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Authoctonous</td>
<td>Very well preserved, low disarticulation</td>
<td>Position of life: dorsal up (5).</td>
<td>Dorsal up</td>
<td>No trend</td>
<td>Dorsal up: 1.00%</td>
<td></td>
<td></td>
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<tr>
<td>Allocronous</td>
<td>Disarticulation and scattering present, depending on time and distance to final deposit</td>
<td>Heterogeneous depending on time since death or time of drift. Majority ventral to lateral up (5, see Fig. S5).</td>
<td>Ventral up – lateral up</td>
<td>One main direction (current-wind) and/or two main directions (tide)</td>
<td>Ventral up: 20.40% Lateral Up: 78.61%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>