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Supplementary Materials for

Cheap gulp foraging of a giga-predator enables efficient exploitation of sparse prey

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References

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Audio S1 to S3
Movies S1 to S6
Data S1

Scaling of lunge costs

Humpback whales are among the smaller rorqual whales and are hypothesized to have both smaller mass specific and absolute costs associated with feeding lunges compared to the larger fin (*Balaenoptera physalus*) and blue whales (*Balaenoptera musculus)* (*6*, *27*, *83–86*). This is due both to their smaller size and the allometric increase in mass-engulfment capacity in larger rorquals, which increases their mechanical costs of lunging (*6*, *87*, *88*). To investigate whether the humpback whales from this study were performing cheaper lunges mass specifically than the larger fin and blue whales we compared our data to that of one tagged fin whale tagged off Tasiilaq, East Greenland during September 2017, with 28.7 hours of tag data (Fig. S13) and two blue whales from a previous published study (bw180827-46 and bw180905-53) (Fig. S14) (*29*, *89*). The same methodology for breath and lunge detection was implemented as previously described. Even though the data consists of only three whales, these show a very similar trend in relative lunge cost compared to that of humpback whales (Fig. S10, Fig. 2). Using the same modelling approach as we used with humpback whales (glmmPQL, poisson family, log link and corrected for autocorrelation but with no random effect of ID since N=1 or 2), the results were: for the fin whale, log(breaths) = 4.1162+0.007753·lunges), slope = 0.53 (estimated from minimum and maximum values) and for the blue whales log(breaths) = 3.4591+0.01528·lunges), slope = 0.56 (estimated from minimum and maximum values). When estimating the absolute cost of a lunge for the fin and blue whales we used the same procedure as for humpback whales but used a body mass of 45t for fin whales (*55*, *90*) and 100t for blue whales (*55*) to calculate TLC (eq. 2). This resulted in estimates for the maximum energy invested in performing a lunge of 1.35MJ for fin whales and 2.98MJ for blue whales, thus the absolute break-even costs increased as expected for these larger whales, but the mass specific costs are very similar. However, as fin and blue whales have a larger engulfment capacity than humpback whales with a mean of 41m^3 and 86 m^3, respectively (*11*, *27*), the density of prey can be as low as 0.01kg m^{-3} and still meet the maximum break-even cost of lunging (~396g of krill for fin whales and ~872g of krill for blue whales), assuming an energetic value for krill of 3800kj kg^{-1} (*9*, *74*). Thus, the estimated break-even prey density for the tagged fin and blue whales is slightly smaller than the value estimated for the larger set of humpback whales in our study. When computing the mechanical work done, it appears that the tagged fin and blue whales with an estimated weight of 45t and 100t perform maximum mechanical work of around 7.5 J/kg, which is slightly smaller, but comparable to the maximum value we estimate for the tagged humpback whales of 8.3J/kg.

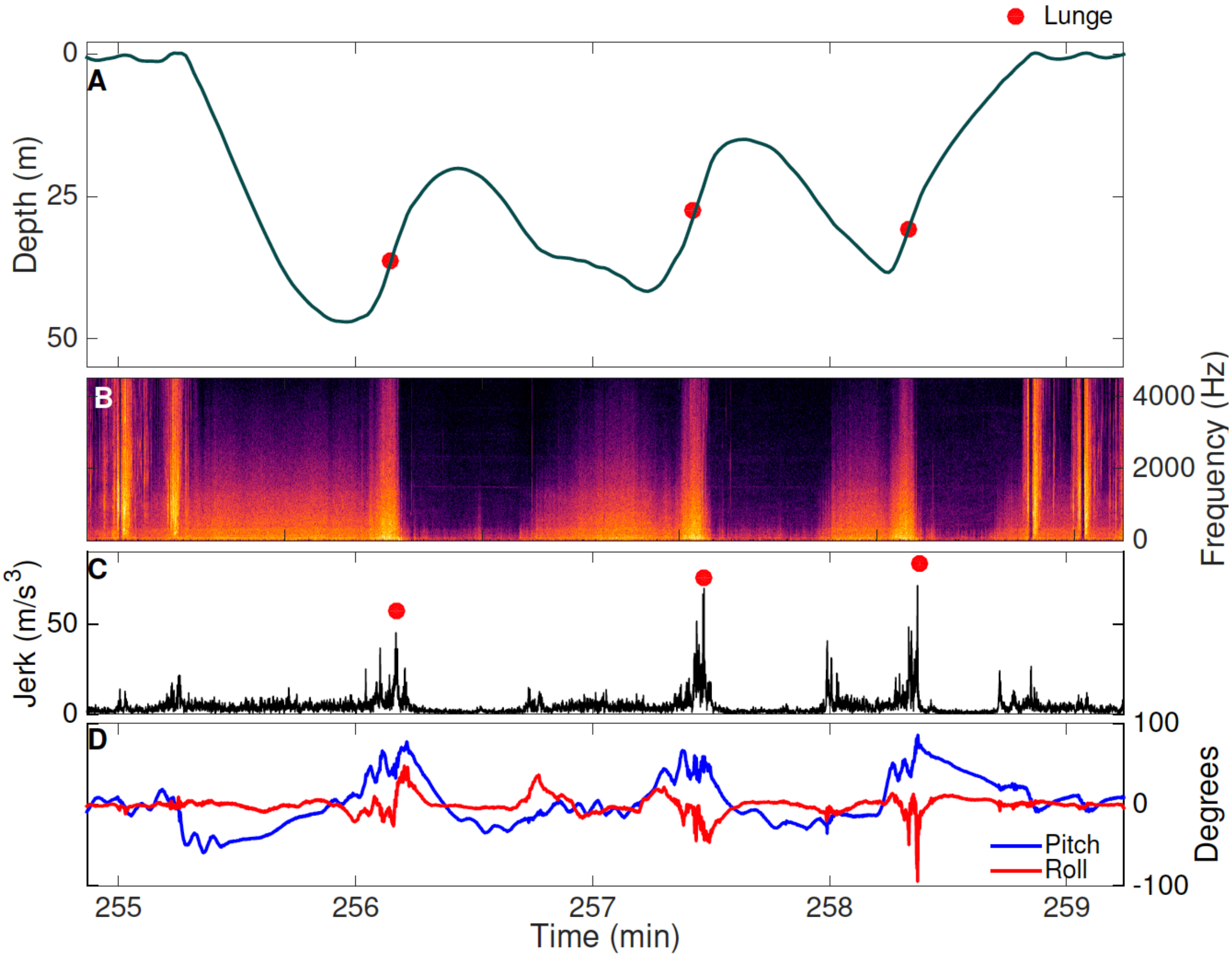


Fig S1. Lunge detection from multi-sensor tag data.

A) dive profile of a humpback whale (mn08_146a) with detected lunges (red circles), B) spectrogram of the sound recording for the same time segment (FFT length: 4096 samples at 96 kHz sampling rate, overlap: 80%, Hann window), C) jerk signal of lunges calculated from accelerometer data, and D) roll and pitch angles during lunge events calculated from accelerometer data.

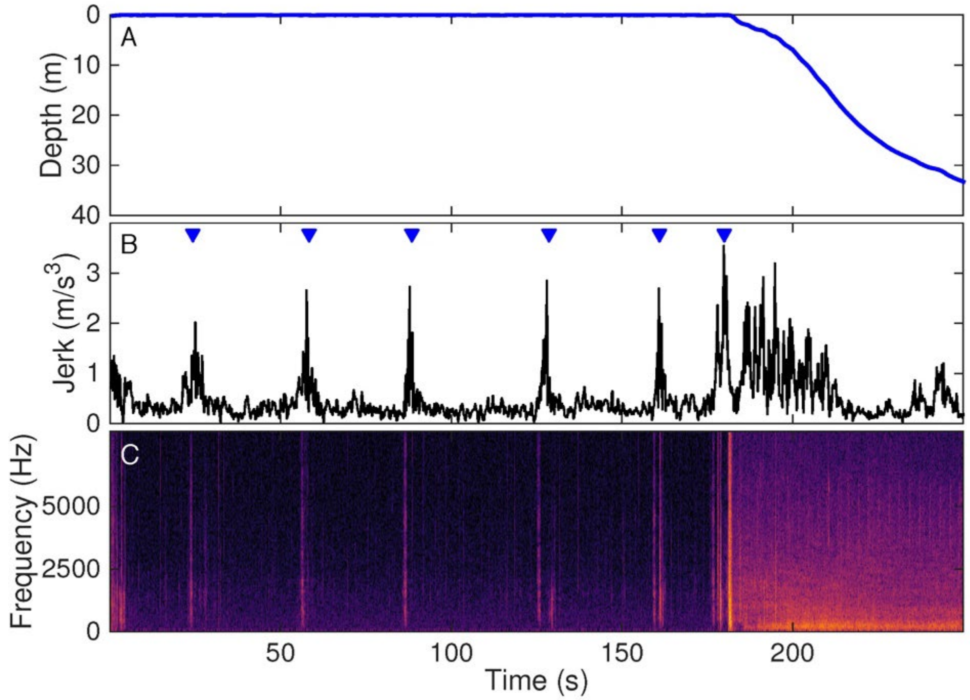


Fig. S2 Breaths sounds of tagged whale. Section of dive profile for mn10_146a showing breath sounds with associated jerk peaks (blue triangles). This figure has an accompanying sound clip (Audio S1). A) dive depth in meters showing a surfacing interval followed by a dive descent, B) the jerk values over the same interval, and C) the corresponding spectrogram for the recorded sound (FFT length: 2048 samples at 96 kHz sampling rate, overlap: 50%, Hann window).

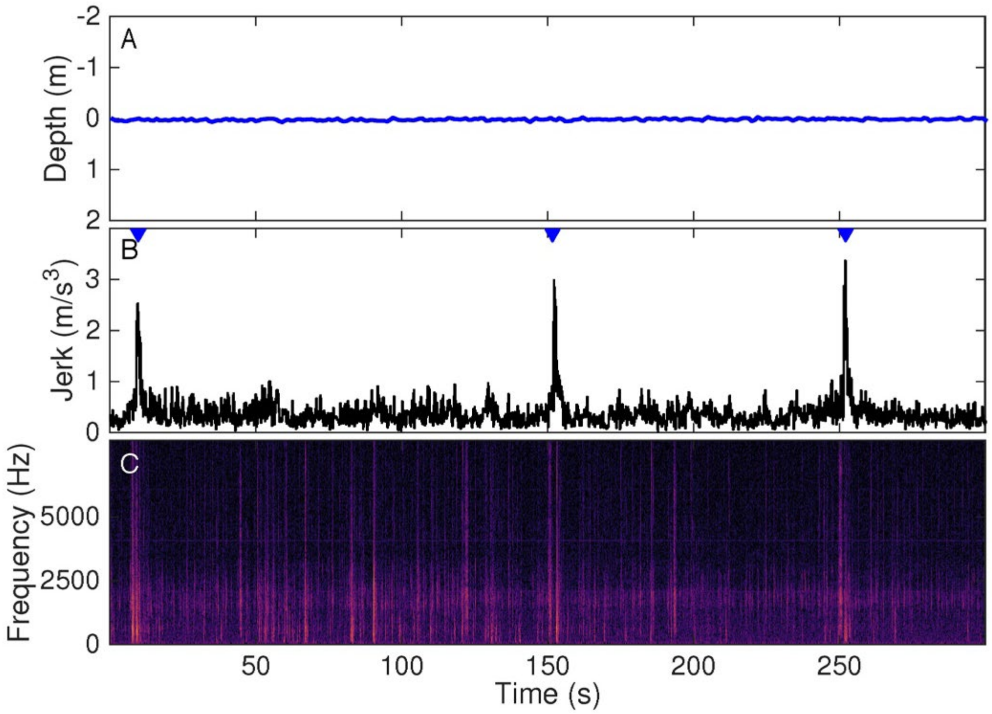


Fig. S3 Breath sounds of tagged whale and conspecifics. Section of audio data for mn10_132a showing breath sounds recorded from both the tagged whale and other nearby animals. Only the breaths of the tagged whale are apparent in the jerk (marked by blue triangles). This figure has an accompanying sound clip (Audio S2). A) shows the dive depth of the tagged whale confirming that it is at the surface, B) jerk values for the same time interval C) spectrogram for the recorded sound (FFT length: 2048 samples at 64 kHz sampling rate, overlap: 50%, Hann window).

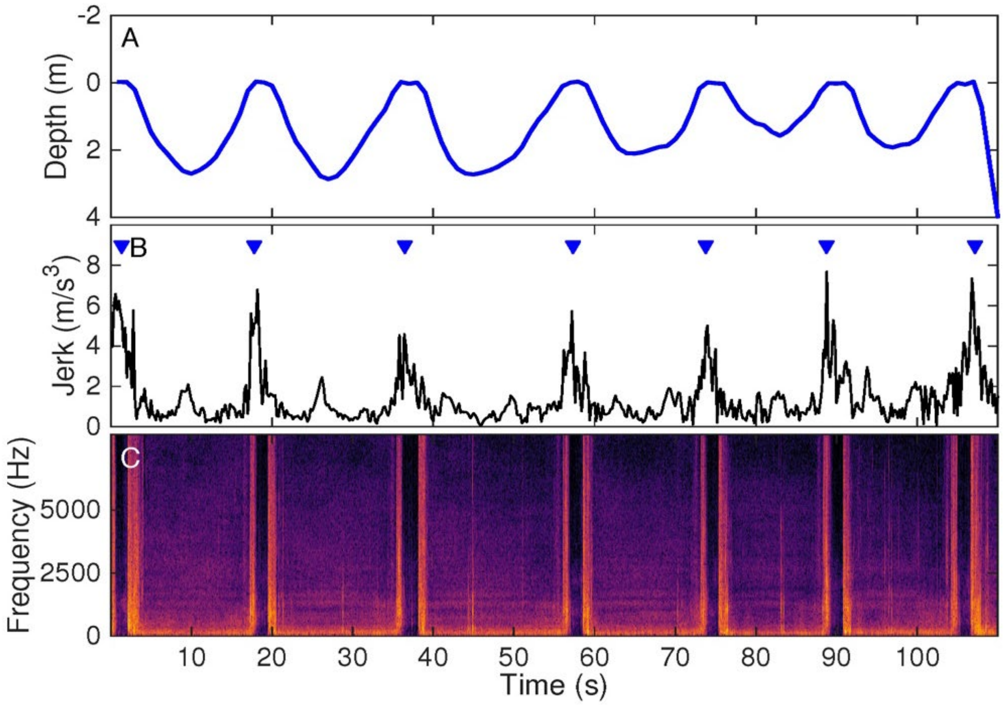


Fig. S4 Breaths of a tagged swimming whale. Section of dive profile of mn10_155a showing an interval of near-surface travel with breaths at each surfacing (Audio S3). A) dive depth, B) corresponding jerk (breaths marked with blue triangles) and C) spectrogram of the recorded sound (FFT length: 2048 samples at 96 kHz sampling rate, overlap: 50%, Hann window).

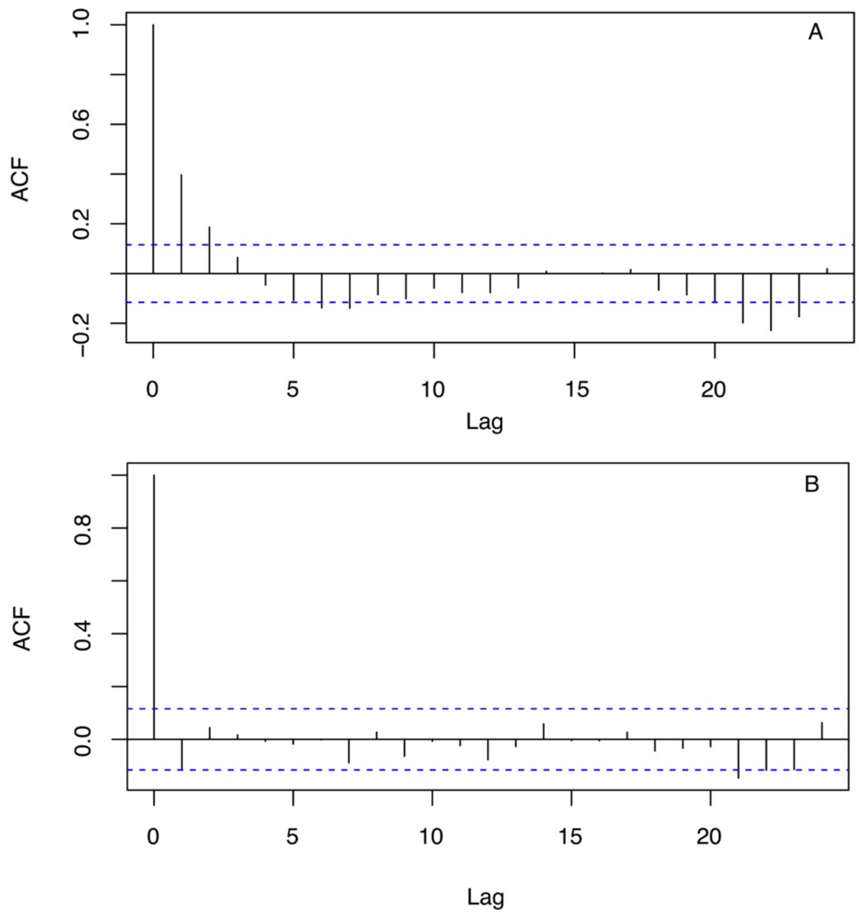


Fig. S5. Autocorrelation function of model residuals showing the temporal correlation. (A) Before and (B) after the inclusion of an auto-regressive structure of lag 1 (AR1) in the GLMM.

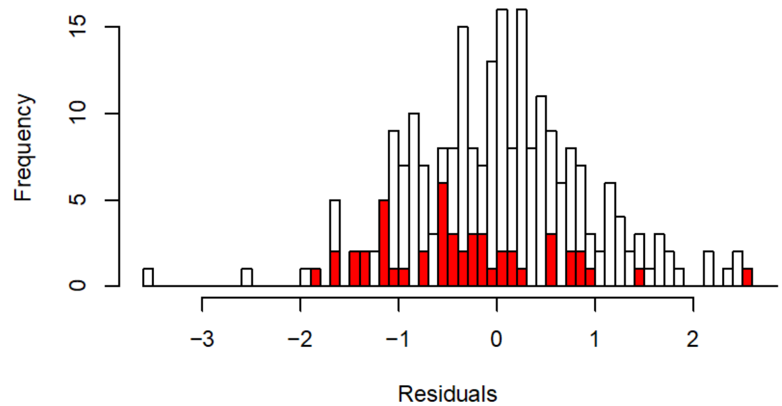


Fig. S6. Histogram of model residuals from the GLMM. Residuals for hourly segments with no lunges are shown in red and segments with lunges are shown in white.

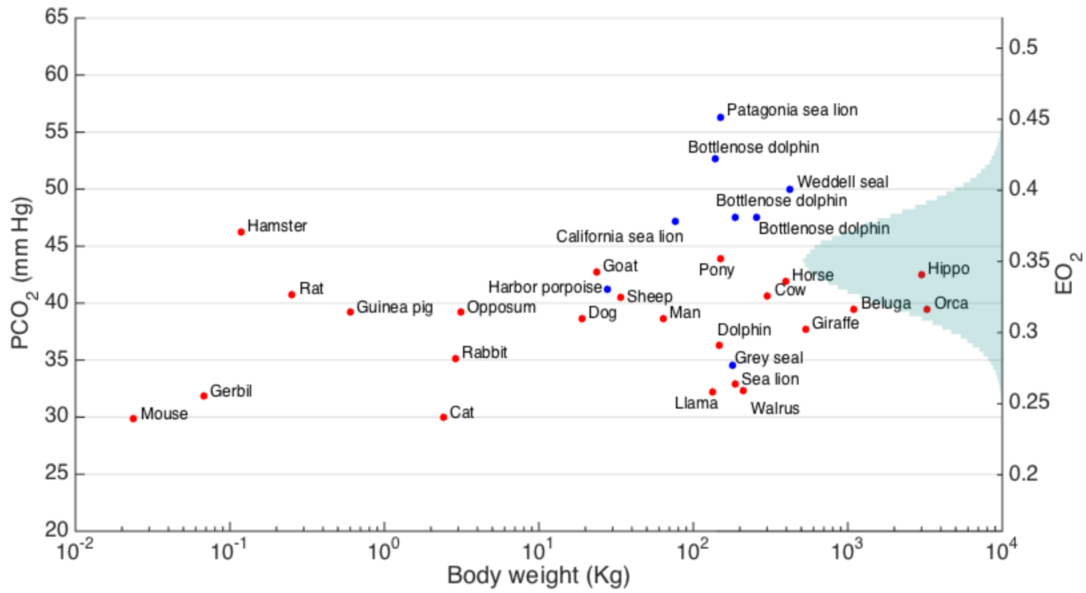


Fig. S7. PaCO₂ distribution in relation to body weight. Data and plot from (*67*) (red dots), with a histogram of our modelled EO_2 (the fractional oxygen uptake), using eq. 6, superimposed. Weddell seal (*Leptonychotes weddellii*) (*91*), bottlenose dolphins (*Tursiops truncatus*) (*42*, *53*, *92*), California sea lion (*Zalophus californianus*) (*93*), Patagonia sea lion (*Otaria flavescens*) (*94*), Grey seal (*Halichoerus grypus*) (*95*) and harbor porpoise (*Phocoena phocoena*) (*54*) (blue dots).

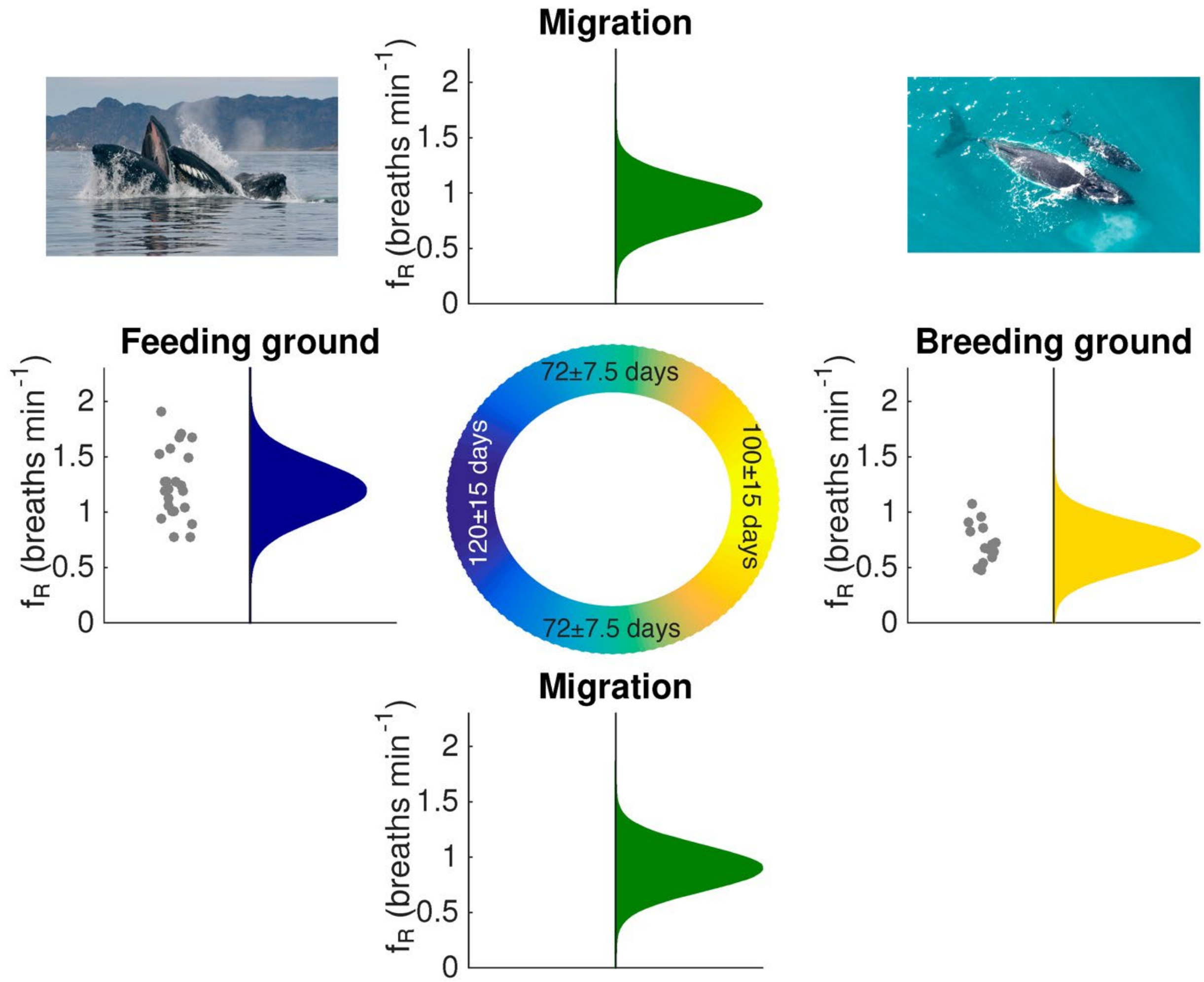


Fig. S8 Yearly life cycle of a humpback whale. The circle represents a year of a humpback whale's life. Each plot depicts estimated probable distributions of breathing rate (*96*). The grey dots in feeding and breeding ground plots represent measured breathing rates in this study and in a previous study (*15*). Respiration data have not been measured during migration.

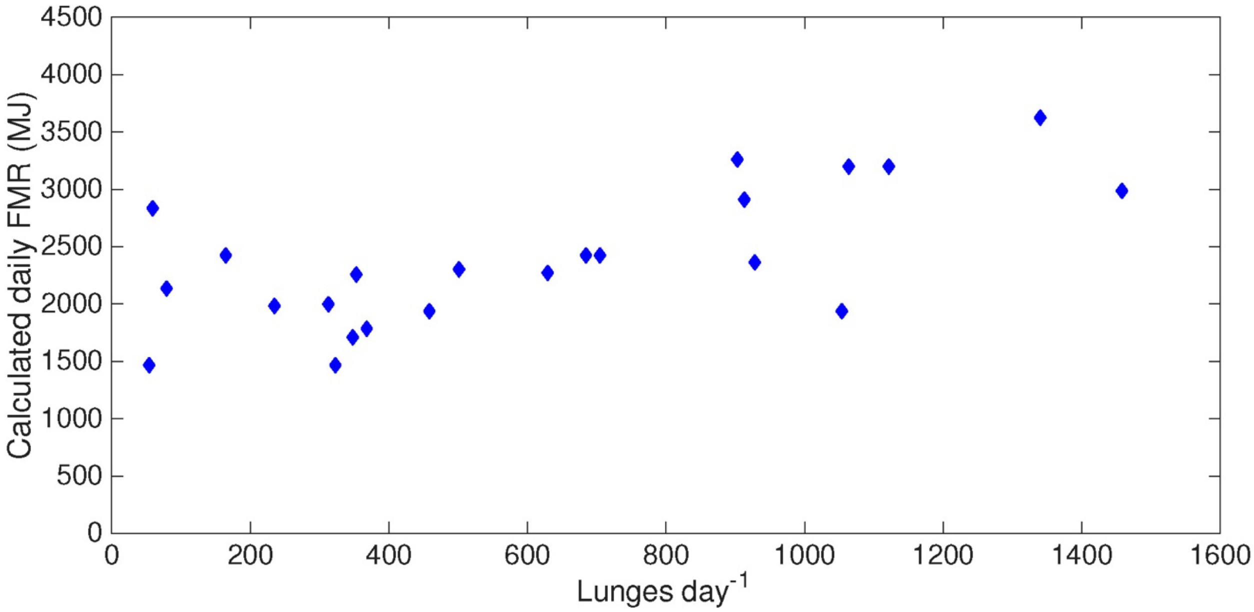


Fig. S9 Calculated FMR on feeding grounds versus lunge rate extrapolated to 24hr. Each point represents the calculated field metabolic rate (FMR) for each tagged whale in Table S1, and the number of lunges detected in the accelerometer and depth data.

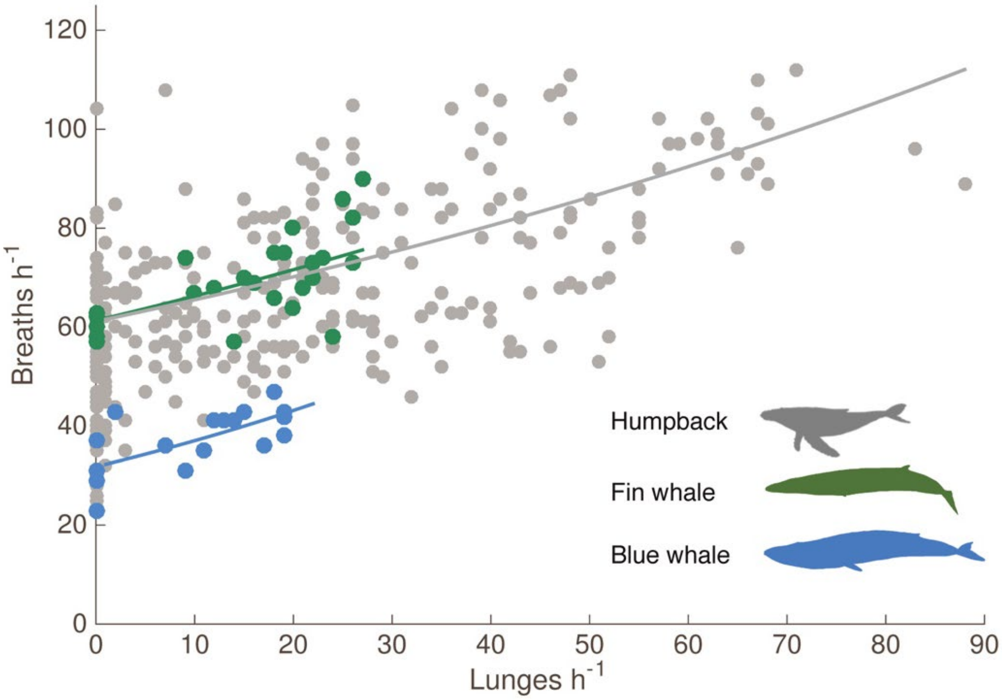


Fig. S10 The relationship between hourly lunge and breath rates for tagged humpback, fin and blue whales. Data come from 23 humpback whales (grey), a single fin whale (tagged for 28.7 hours off Tasiilaq, Greenland, green), and two blue whales (*89*) (blue).

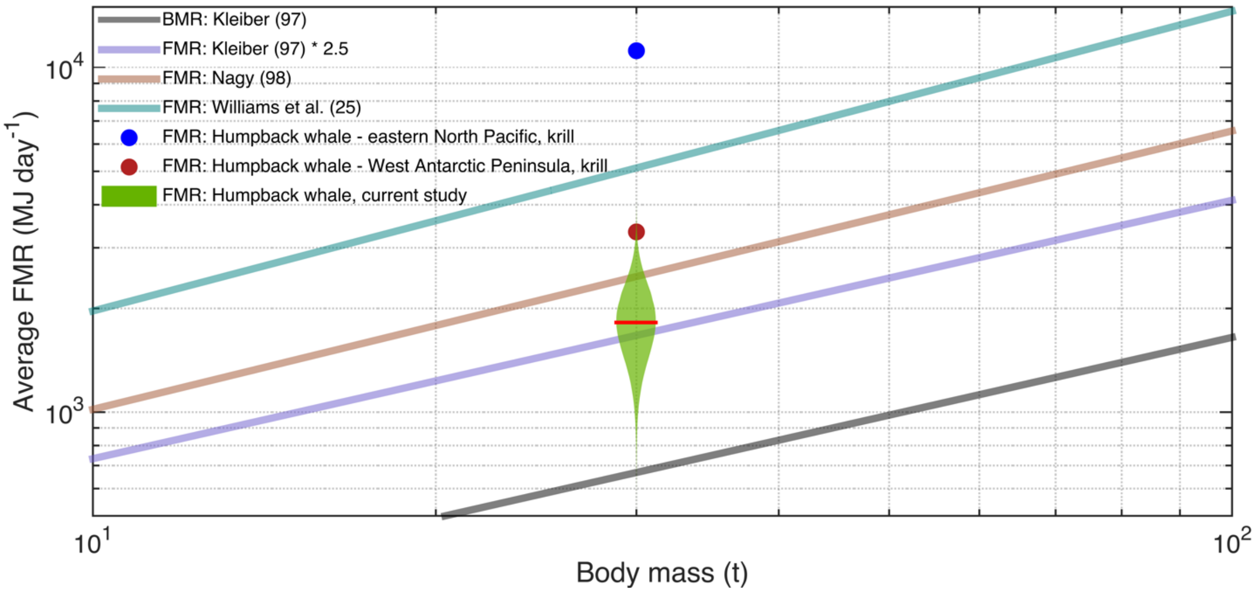
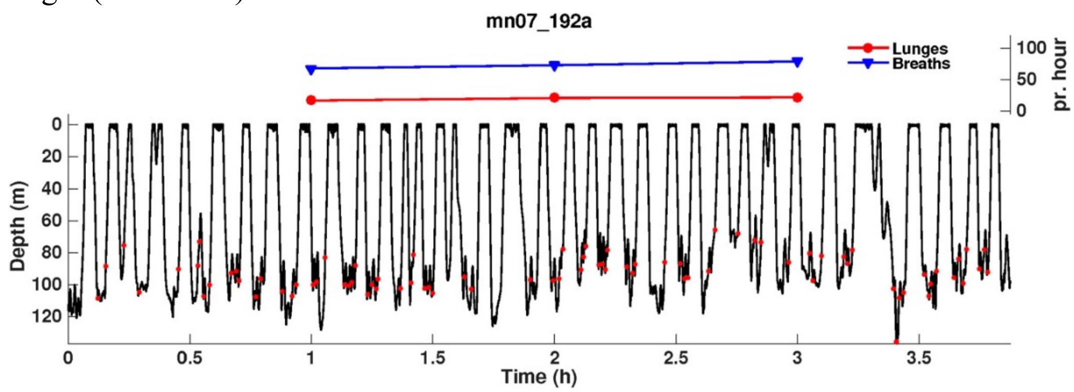
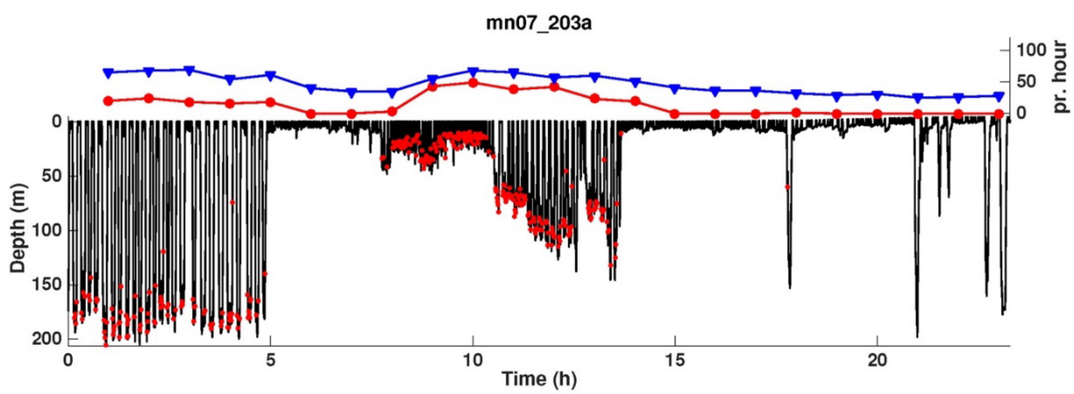
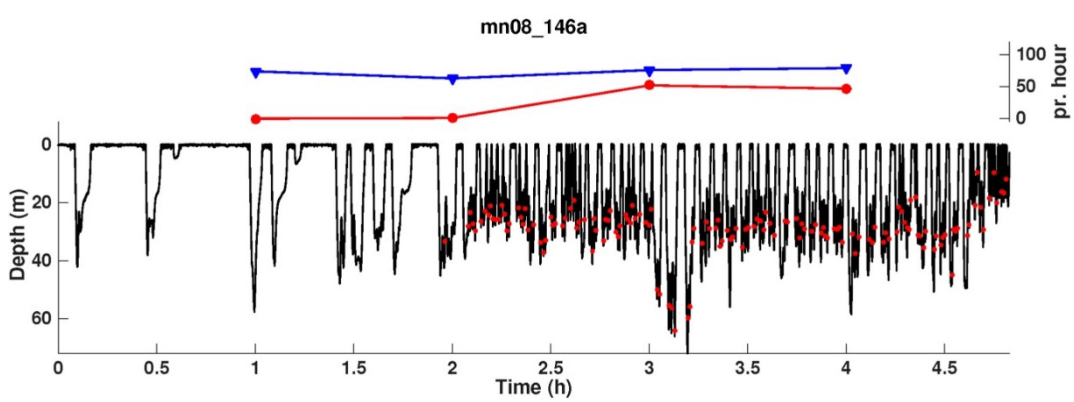


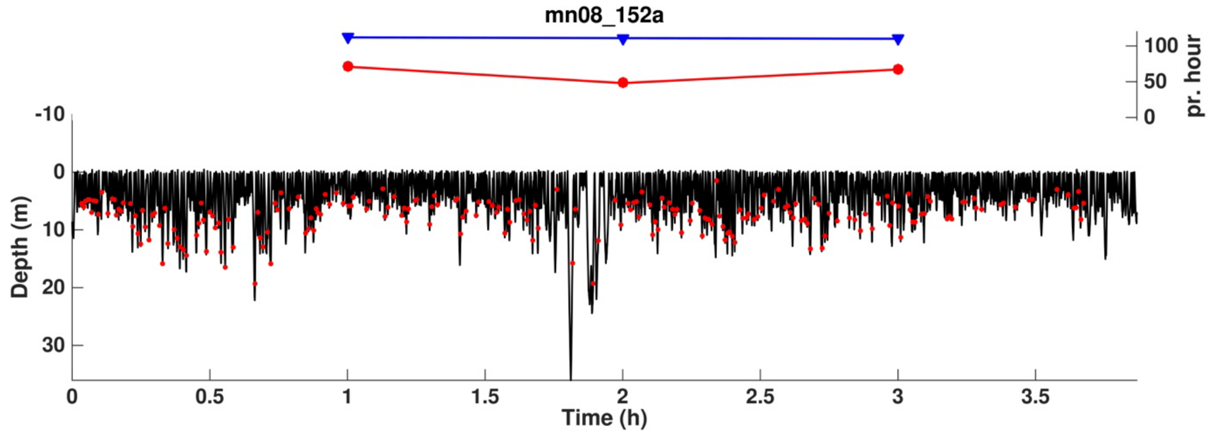
Fig. S11. Estimated FMR of free-swimming humpback whales compared to scaling equations proposed for marine mammals. Violin plot of daily average field metabolic rate of 30t humpback whales is based on our estimated annual energy expenditure (Fig. 3). Blue dot shows estimated daily FMR of humpback whales targeting krill in the eastern North Pacific and the red dot shows estimated daily FMR of humpback whales off the West Antarctic Peninsula targeting krill (*11*). These two data points arise from yearly prey ingestion and are corrected for somatic growth and reproduction costs and scaled to a 30t whale. Each line represents proposed scaling equations for the FMR of marine mammals (*25*, *97*, *98*).

Fig. S12. Dive profiles of all tagged humpback whales included in our analysis. The title of each sub-plot corresponds to whale ID in Table S1. The top panel in each figure displays lunge and breath counts in 1 hour time blocks. The lower panel shows the dive profile with detected lunges (red circles).





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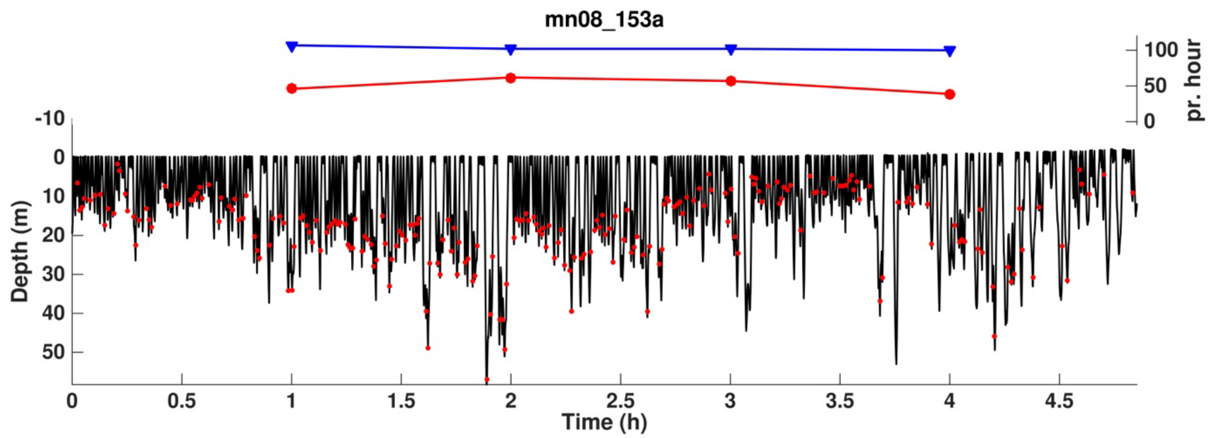
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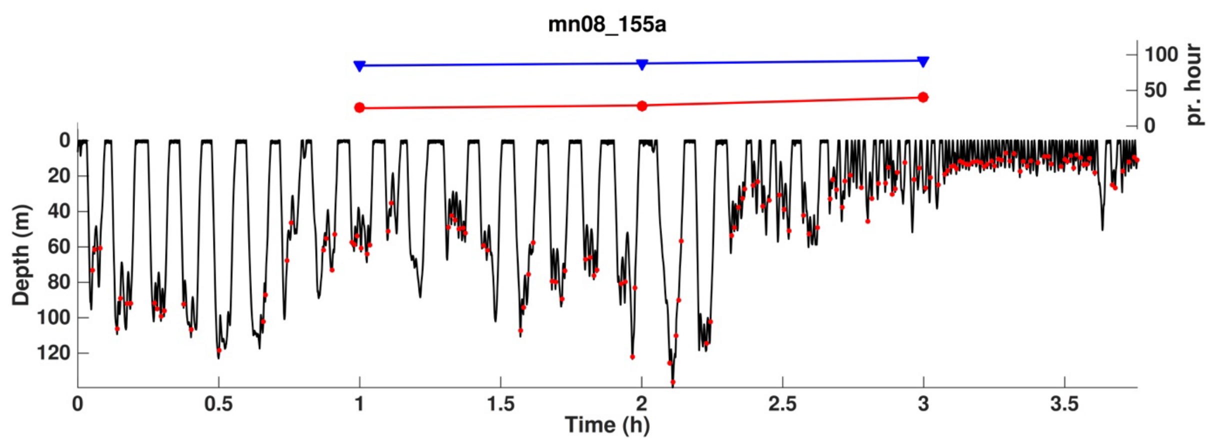
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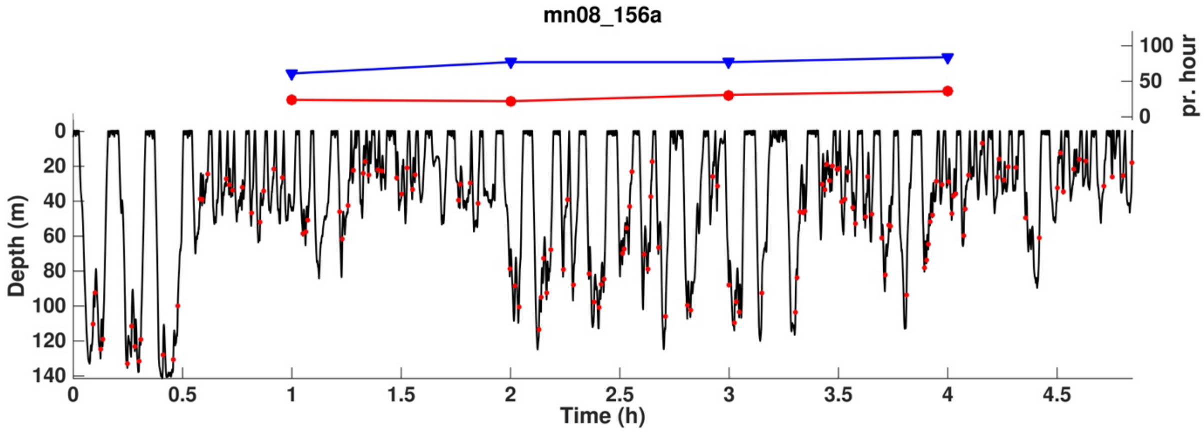
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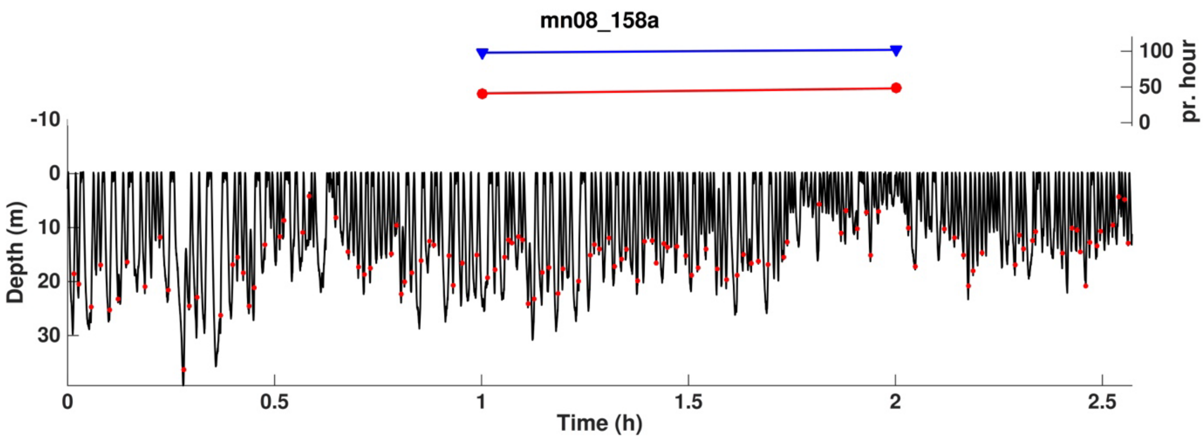
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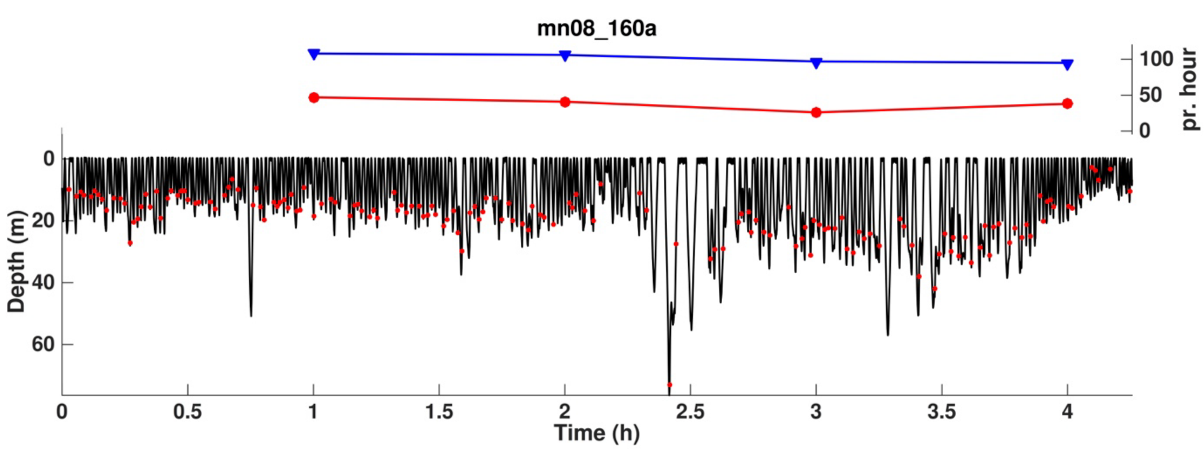
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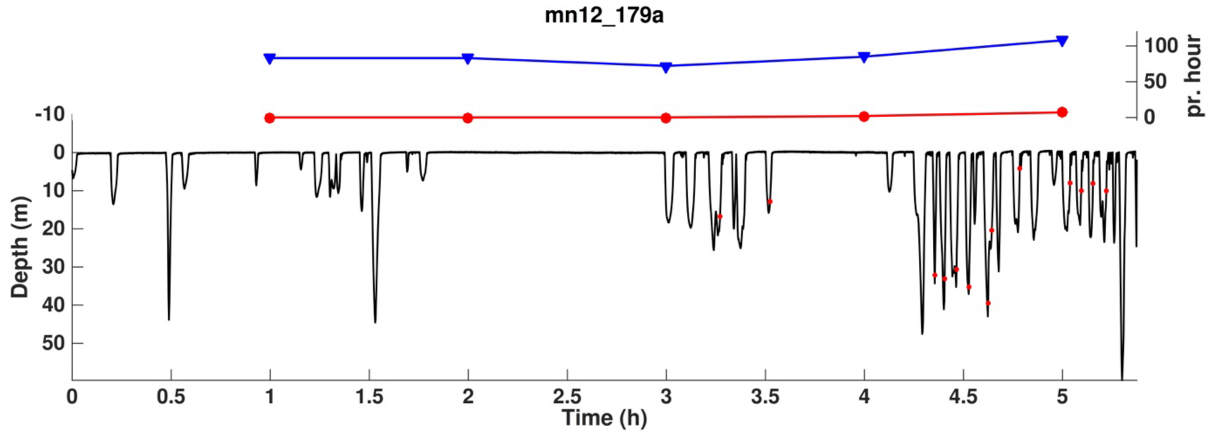
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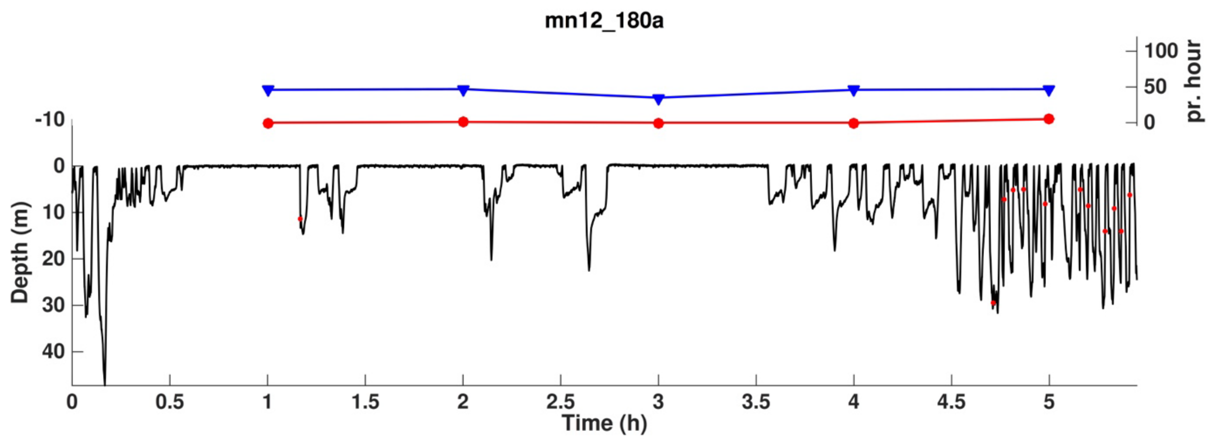
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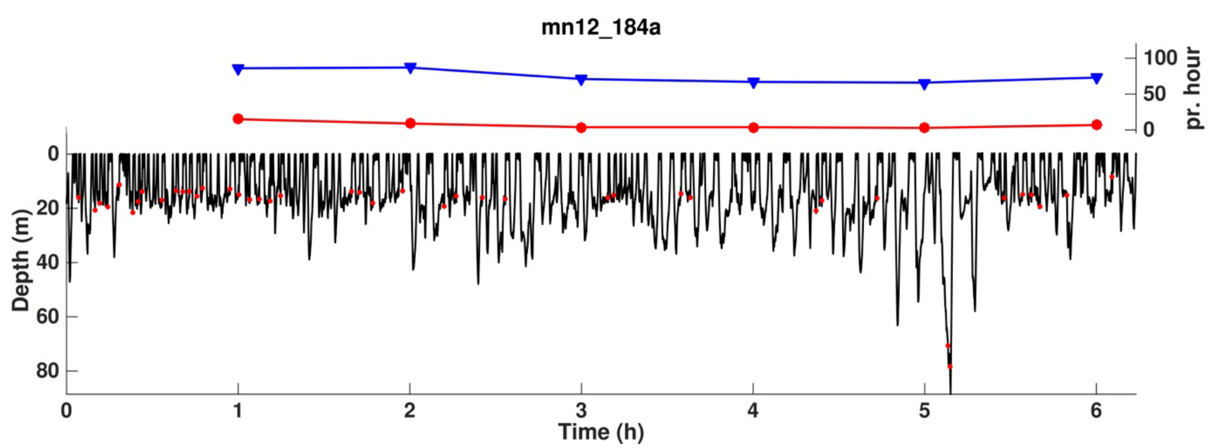
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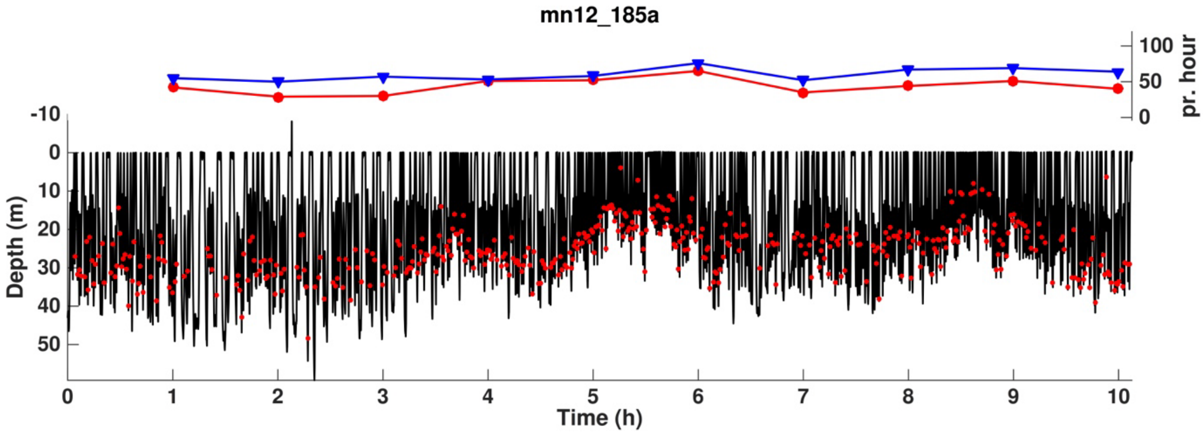
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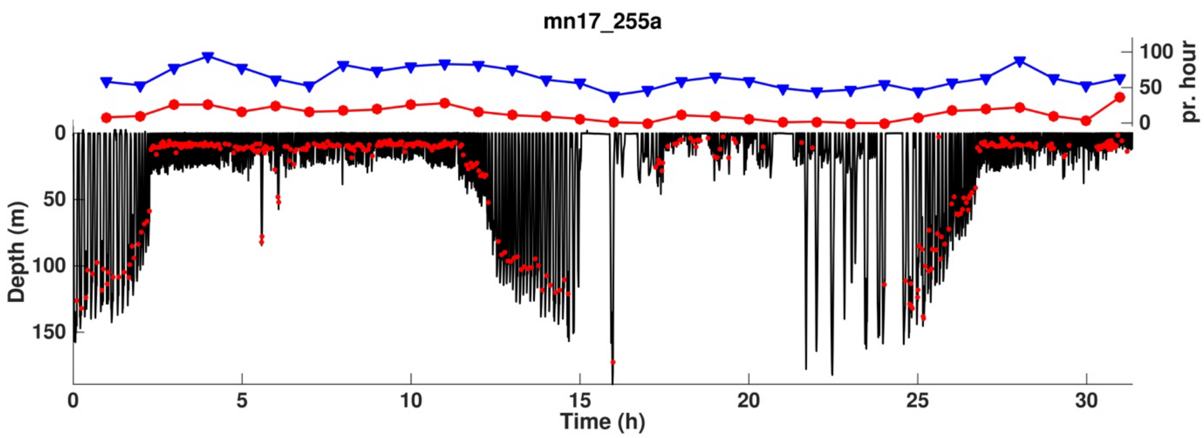
Time (h)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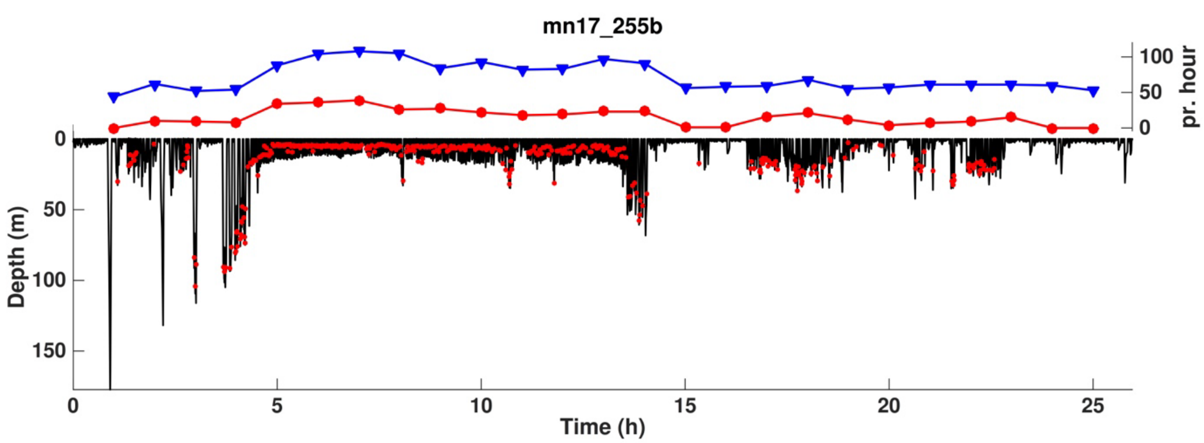
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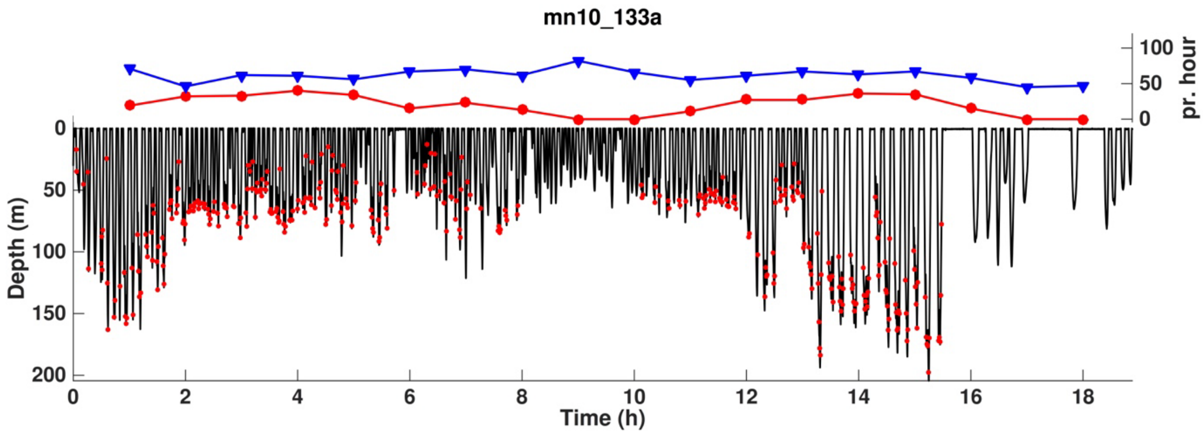
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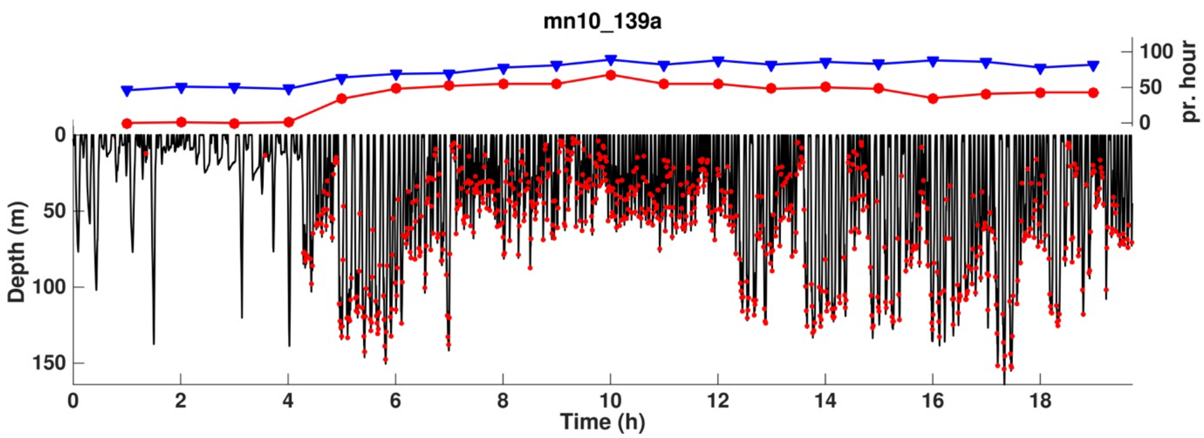
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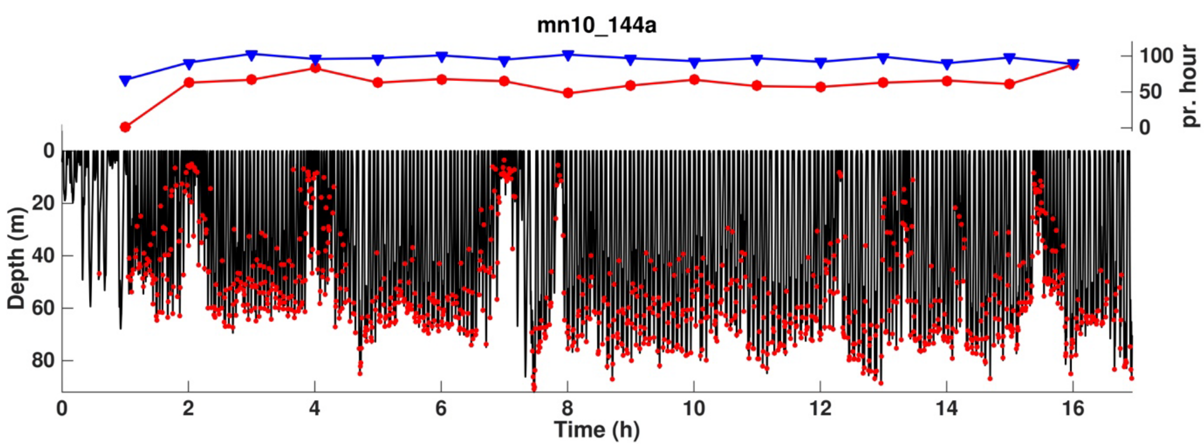
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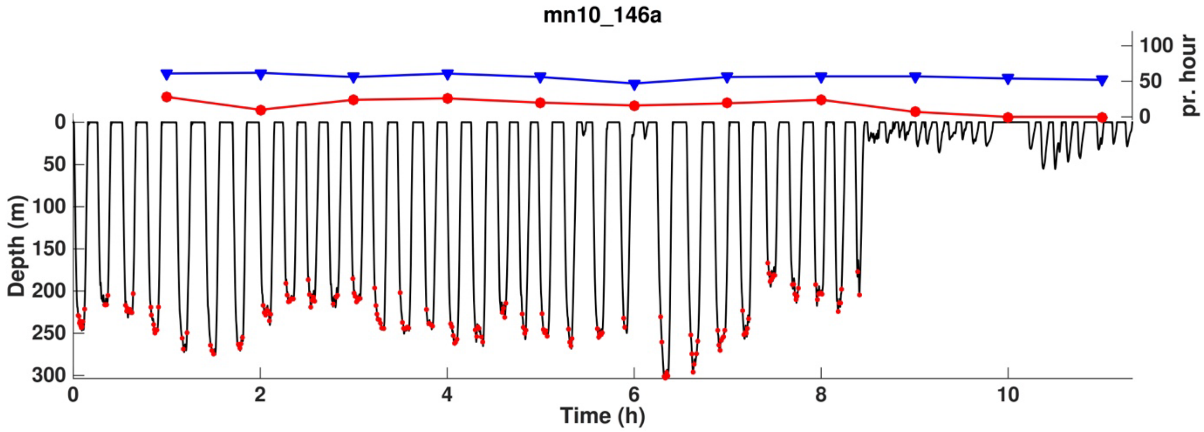
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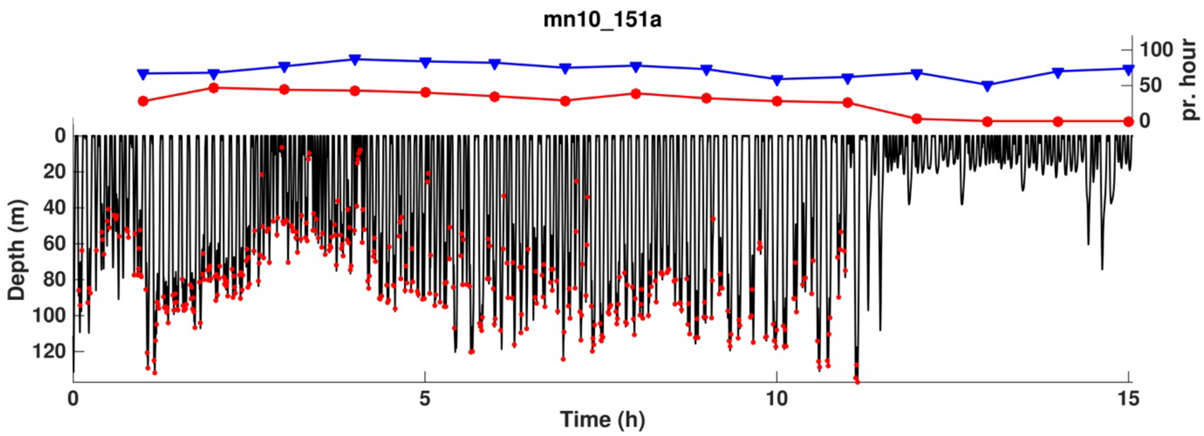
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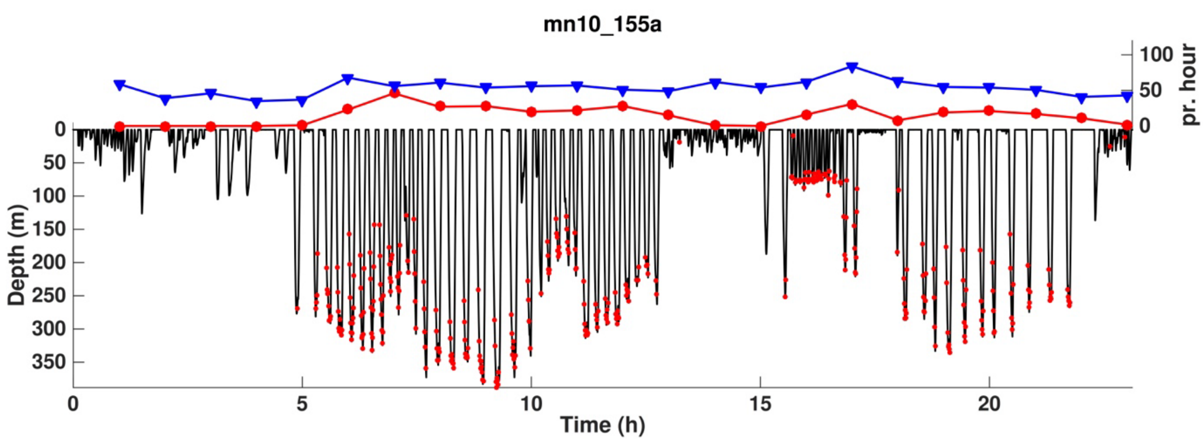
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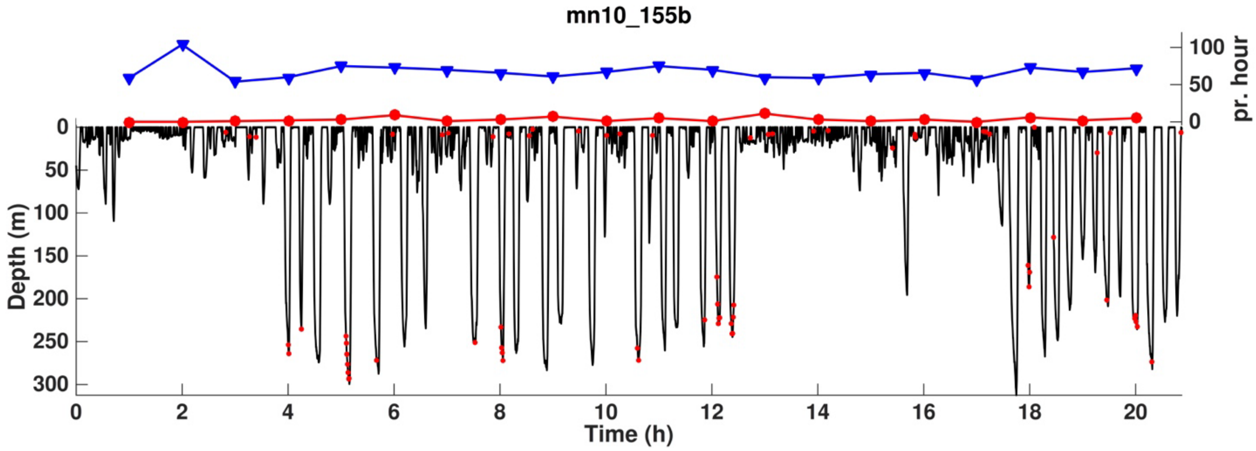
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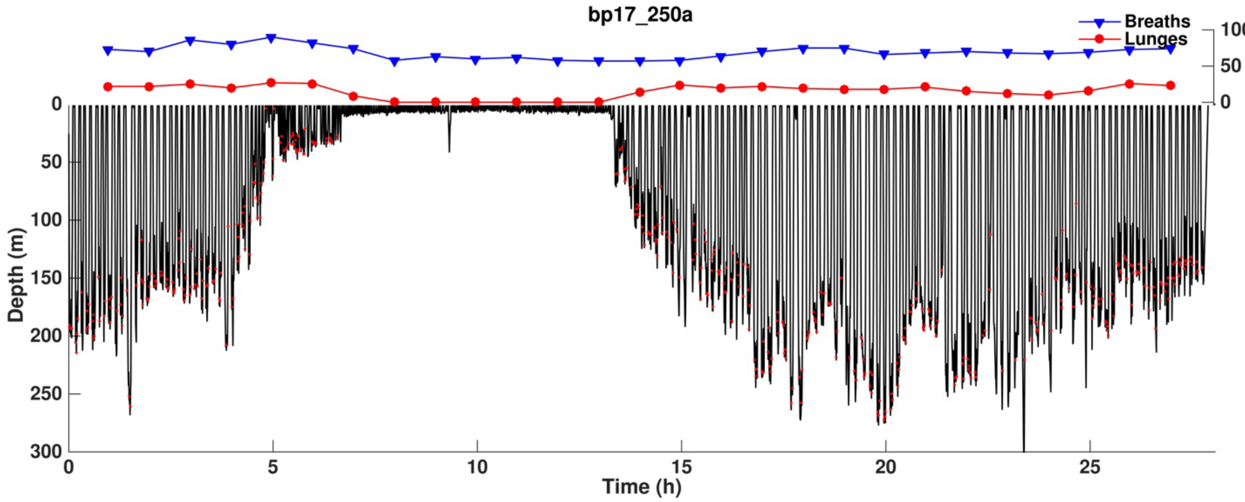

Fig. S13. Dive profile of a tagged fin whale. Title of plot corresponds to whale ID. First panel displays lunge and breath counts in 1 hour time blocks. Second panel shows the dive profile with lunges (red circles).

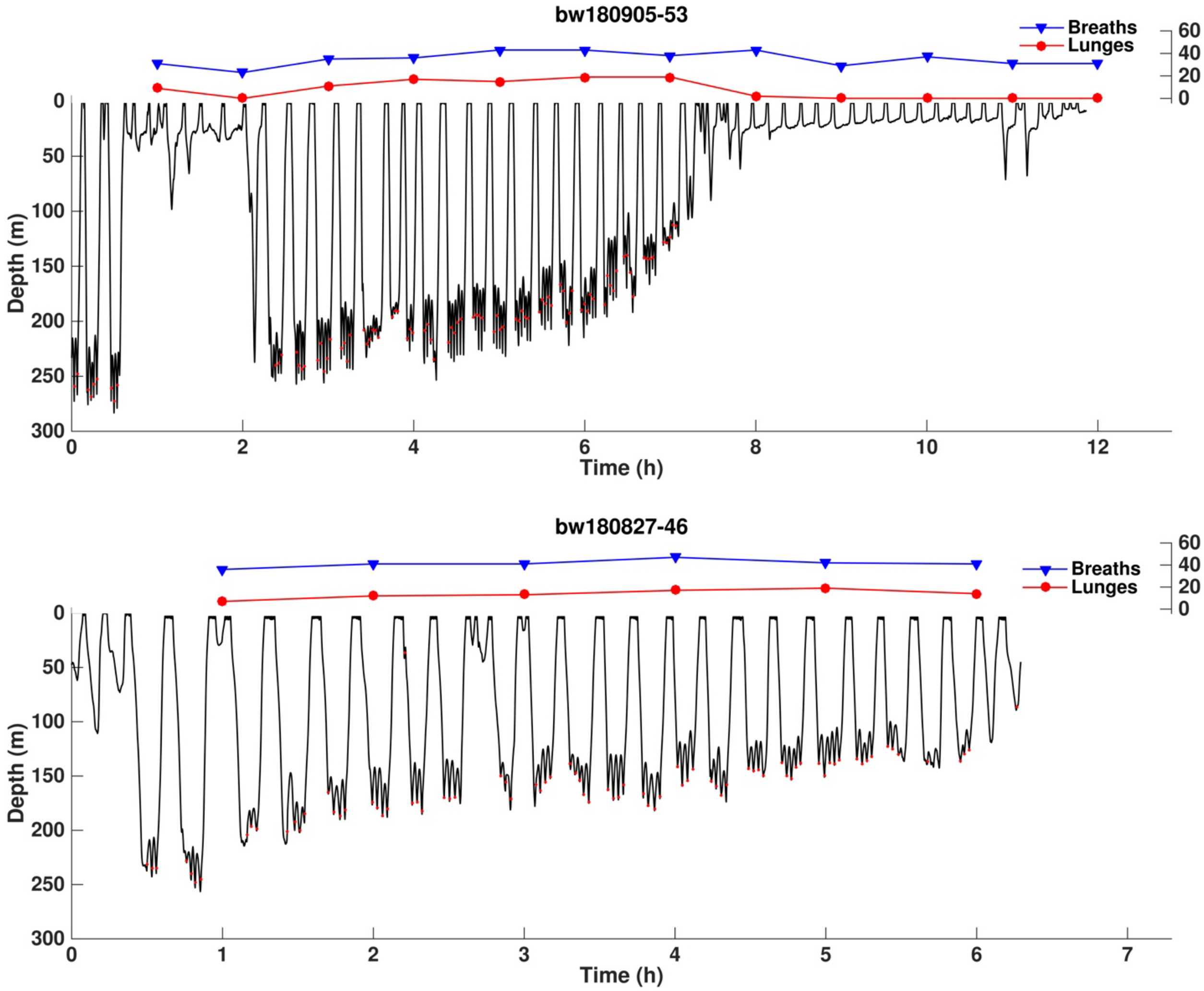

Fig. S14. Dive profile of tagged blue whales (*89*). Title of plot corresponds to whale ID. First panel displays lunge and breath counts in 1 hour time blocks. Second panel shows the dive profile with lunges (red circles).

Table S1.

Tag deployment details and data overview

Whale ID	Tagging location	Tag deployment duration (h)	Analyzed data interval (start-end, s)	Breathing rate (min^{-1})	Lunge rate (h^{-1})
Mn07_192a	Nuuk fjord, Greenland	4.9	3600-17550	1.21	20.9
Mn07_203a	Nuuk fjord, Greenland	24.3	3600-87399	0.77	13.5
Mn08_146a	Nuuk fjord, Greenland	5.8	3600-20984	1.27	29.4
Mn08_152a	Nuuk fjord, Greenland	4.9	3600-17525	1.90	55.8
Mn08_153a	Nuuk fjord, Greenland	5.9	3600-21071	1.68	46.8
Mn08_155a	Nuuk fjord, Greenland	4.8	3600-17126	1.53	38.1
Mn08_156a	Nuuk fjord, Greenland	5.8	3600-21038	1.27	28.5
Mn08_158a	Nuuk fjord, Greenland	3.6	3600-12857	1.68	44.3
Mn08_160a	Nuuk fjord, Greenland	5.3	3600-18923	1.71	37.6
Mn10_133a	Wilhelmina Bay, Antarctica	22.7	13900-81859	1.01	19.1
Mn10_139a	Wilhelmina Bay, Antarctica	20.7	3600-74564	1.24	38.7
Mn10_144a	Wilhelmina Bay, Antarctica	17.9	3600-64560	1.57	60.7
Mn10_146a	Wilhelmina Bay, Antarctica	20	31132-71912	0.94	15.4
Mn10_151a	Wilhelmina Bay, Antarctica	20.3	19000-73190	1.19	26.2
Mn10_155a	Wilhelmina Bay, Antarctica	24.1	3600-86827	0.89	14.5
Mn10_155b	Wilhelmina Bay, Antarctica	21.9	3600-78730	1.12	3.3
Mn12_179a	Disko bay, Greenland	6.4	3600-22952	1.49	2.4
Mn12_180a	Disko bay, Greenland	6.4	3600-23213	0.77	2.2
Mn12_184a	Disko bay, Greenland	7.2	3600-26032	1.27	6.9
Mn12_185a	Disko bay, Greenland	11.1	3600-40056	1.01	43.9

Mn17_251a 44	Tasiilaq, Greenland	34.9	3600-116457	1.04	9.8
Mn17_255a 42	Tasiilaq, Greenland	32.3	3600-97060	1.05	13
Mn17_255b 43	Tasiilaq, Greenland	26.9	3600-125889	1.18	14.7

Movie S1.
Onboard video of a bottom lunge. All video samples were recorded with a CATS tag on humpback whales.

Movie S2.
Onboard video of a bubble-net lunge.

Movie S3.
Onboard video of a lunge feeding on fish.

Movie S4.
Onboard video of a lunge with dense prey.

Movie S5.
Onboard video of a whale swimming and breathing.

Movie S6.
Onboard video of a logging whale breathing.

Audio S1.
Breath sounds recorded by a Dtag attached to a logging humpback whale.

Audio S2.
Breath sounds from the tagged whale and nearby conspecifics recorded by a Dtag.

Audio S3.
Breath sounds recorded by a Dtag attached to a travelling humpback whale.

Data S1
Hourly counts of lunges and breaths for each individual whale

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