

Diel vertical migration and central place foraging in benthic predators

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Supplement 1.

Supplementary data

Table S1: Datasets with selected central place events

| <i>Tag</i> | <i>Species</i> | <i>Sex</i> | <i>Release Date</i> | <i>Length (mm)</i> | <i>Disk (mm)</i> | <i>Release Latitude</i> | <i>Release Longitude</i> | <i>Recapture Date</i> | <i>Recapture Latitude</i> | <i>Recapture Longitude</i> | <i>Days At Liberty</i> | <i>Displacement (km)</i> | <i>No of events</i> |
|------------|----------------|------------|---------------------|--------------------|------------------|-------------------------|--------------------------|-----------------------|---------------------------|----------------------------|------------------------|--------------------------|---------------------|
| A01775 | Raja brachyura | F | 2010-01-05 | 705 | 478 | 50.3679 | -4.1734 | 2010-04-09 | 50.2734 | -3.9342 | 91 | 19.99 | 4 |
| A01840 | Raja brachyura | M | 2010-04-12 | 686 | 516 | 50.3008 | -4.1165 | 2010-05-17 | 50.2549 | -4.0656 | 33 | 6.26 | 2 |
| A01846 | Raja brachyura | M | 2010-04-12 | 624 | 440 | 50.3008 | -4.1165 | 2010-06-13 | 50.0353 | -4.0457 | 60 | 29.99 | 5 |
| A01852 | Raja brachyura | F | 2010-04-15 | 825 | 593 | 50.2601 | -3.9339 | 2010-07-19 | 50.2558 | -3.875 | 94 | 4.22 | 1 |
| A05886 | Raja brachyura | F | 2010-04-15 | 600 | 419 | 50.2591 | -4.0203 | 2010-07-30 | 50.3408 | -4.2742 | 105 | 20.22 | 6 |
| A05908 | Raja brachyura | F | 2010-06-09 | 832 | 596 | 50.33 | -3.133333 | 2010-08-05 | 50.32144 | -4.070748 | 55 | 66.63 | 7 |
| A05927 | Raja brachyura | F | 2010-07-13 | 681 | 504 | 50.3175 | -4.1332 | 2010-09-18 | 50.2565 | -4.9307 | 65 | 57.13 | 2 |
| A05950 | Raja brachyura | F | 2010-11-23 | 737 | 520 | 50.299 | -4.1061 | 2012-10-10 | 50.1563 | -3.8983 | 685 | 21.70 | 1 |
| A05962 | Raja brachyura | M | 2010-11-23 | 760 | 539 | 50.299 | -4.1061 | 2011-11-20 | 50.25 | -3.575 | 360 | 38.18 | 28 |
| A06014 | Raja brachyura | F | 2010-11-23 | 632 | 452 | 50.299 | -4.1061 | 2011-01-25 | -- | -- | 61 | -- | 4 |
| B0357a | Raja brachyura | M | 2012-01-11 | 722 | 520 | 50.334 | -4.1635 | 2012-04-27 | 50.2513 | -3.9037 | 101 | 20.65 | 2 |
| A01711a | Raja clavata | F | 2009-10-02 | 884 | 575 | 50.3318 | -4.1672 | 2010-02-07 | 50.3281 | -4.1912 | 117 | 1.75 | 3 |
| A01735 | Raja clavata | F | 2009-09-04 | 840 | 574 | 50.3334 | -4.1959 | 2009-12-05 | 50.328 | -4.1843 | 89 | 1.02 | 46 |
| A01736 | Raja clavata | M | 2009-09-08 | 520 | 352 | 50.3074 | -4.2193 | 2010-09-17 | 50.2144 | -4.2882 | 372 | 11.45 | 13 |
| A01764 | Raja clavata | F | 2008-06-17 | 684 | 471 | 50.3231 | -4.2411 | 2011-06-02 | 50.3118 | -4.2522 | 1052 | 1.48 | 31 |
| A01767 | Raja clavata | F | 2008-07-16 | 543 | 375 | 50.39 | -4.2006 | 2010-06-04 | 50.3413 | -4.1571 | 688 | 6.24 | 3 |
| A01770 | Raja clavata | F | 2008-10-17 | 883 | 624 | 50.3128 | -4.1322 | 2008-12-16 | 50.2689 | -4.0654 | 41 | 6.82 | 12 |
| A01770a | Raja clavata | M | 2009-10-01 | 586 | 394 | 50.3365 | -4.1563 | 2010-05-15 | 50.3296 | -4.1923 | 225 | 2.68 | 2 |

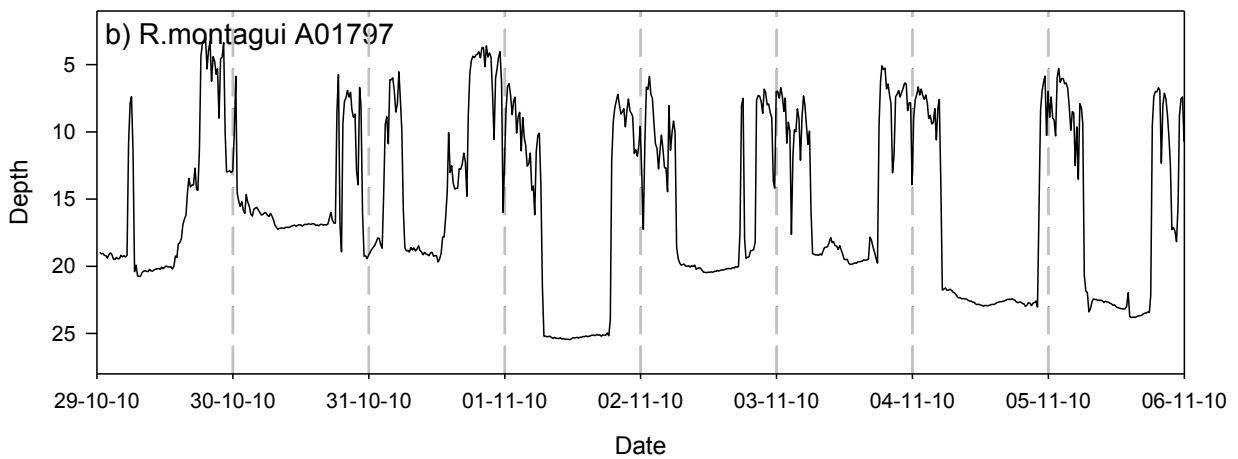
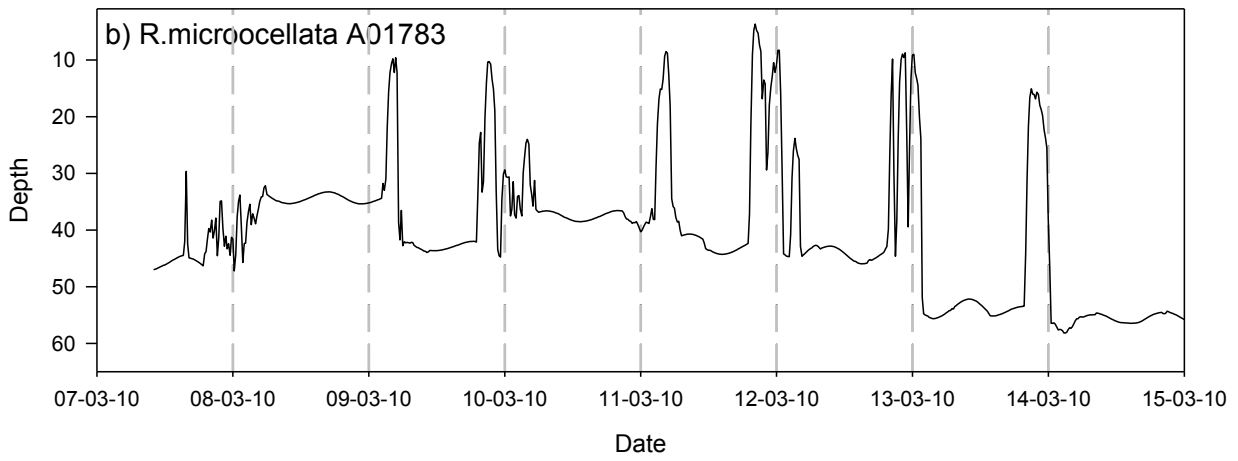
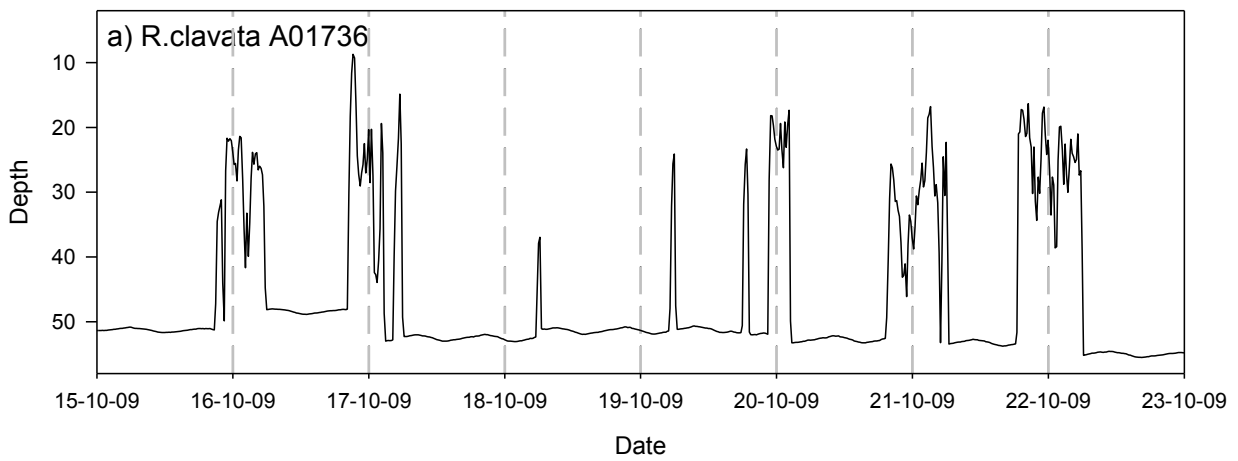
| <i>Tag</i> | <i>Species</i> | <i>Sex</i> | <i>Release Date</i> | <i>Length (mm)</i> | <i>Disk (mm)</i> | <i>Release Latitude</i> | <i>Release Longitude</i> | <i>Recapture Date</i> | <i>Recapture Latitude</i> | <i>Recapture Longitude</i> | <i>Days At Liberty</i> | <i>Displacement (km)</i> | <i>No of events</i> |
|------------|--------------------|------------|---------------------|--------------------|------------------|-------------------------|--------------------------|-----------------------|---------------------------|----------------------------|------------------------|--------------------------|---------------------|
| A01773 | Raja clavata | F | 2009-11-05 | 834 | 568 | 50.3353 | -4.1673 | 2010-05-23 | 50.3024 | -4.1654 | 163 | 3.67 | 1 |
| A05888 | Raja clavata | F | 2010-04-21 | 558 | 413 | 50.3402 | -4.1614 | 2010-07-22 | 50.3413 | -4.1571 | 89 | 0.33 | 26 |
| A05895 | Raja clavata | F | 2011-02-08 | 815 | 585 | 50.2946 | -4.1289 | 2011-05-15 | 50.25 | -3.9167 | 94 | 15.89 | 1 |
| A05959 | Raja clavata | M | 2010-11-01 | 840 | 508 | 50.3623 | -4.1874 | 2011-03-27 | 50.3628 | -4.1349 | 143 | 3.73 | 2 |
| A05961 | Raja clavata | F | 2010-11-03 | 865 | 601 | 50.3621 | -4.1905 | 2011-01-30 | -- | -- | 86 | -- | 1 |
| A05984 | Raja clavata | M | 2010-04-19 | 553 | 384 | 50.3485 | -4.1537 | 2010-04-22 | 50.3413 | -4.1571 | 0 | 0.84 | 4 |
| A06001 | Raja clavata | F | 2010-06-09 | 534 | 376 | 50.3307 | -4.1336 | 2010-07-25 | -- | -- | 44 | -- | 15 |
| A06009 | Raja clavata | F | 2010-08-12 | 566 | 390 | 50.2475 | -3.991 | 2010-08-18 | 50.283 | -4.1475 | 5 | 11.82 | 23 |
| A06015 | Raja clavata | F | 2010-11-23 | 479 | 362 | 50.299 | -4.1061 | 2011-02-11 | 50.225 | -4.0583 | 78 | 8.91 | 47 |
| B0324 | Raja clavata | F | 2012-05-23 | 818 | 590 | 50.2901 | -4.2749 | 2012-07-10 | 50.3245 | -4.2362 | 46 | 4.72 | 1 |
| B0334 | Raja clavata | M | 2011-05-18 | 527 | 356 | 50.3619 | -4.18 | 2011-12-29 | -- | -- | 223 | -- | 15 |
| B0336 | Raja clavata | M | 2011-05-18 | 709 | 472 | 50.3619 | -4.18 | 2013-01-24 | 50.2872 | -3.9227 | 615 | 20.09 | 1 |
| B0340 | Raja clavata | F | 2011-05-19 | 728 | 512 | 50.3261 | -4.254 | 2012-06-26 | -- | -- | 354 | -- | 4 |
| B0342 | Raja clavata | F | 2011-07-26 | 694 | 482 | 50.3083 | -4.1823 | 2012-04-03 | -- | -- | 249 | -- | 2 |
| B0343 | Raja clavata | F | 2011-07-26 | 781 | 551 | 50.3083 | -4.1823 | 2011-09-01 | 50.335 | -4.245 | 34 | 5.36 | 10 |
| B0344 | Raja clavata | F | 2011-07-26 | 728 | 508 | 50.3083 | -4.1823 | 2012-04-28 | -- | -- | 274 | -- | 13 |
| B0345 | Raja clavata | F | 2011-07-26 | 862 | 587 | 50.3083 | -4.1823 | 2012-04-24 | -- | -- | 270 | -- | 5 |
| B0347 | Raja clavata | F | 2011-07-26 | 835 | 552 | 50.3083 | -4.1823 | 2012-03-31 | 50.3317 | -4.2414 | 246 | 4.94 | 7 |
| B0348 | Raja clavata | F | 2011-07-26 | 859 | 578 | 50.3083 | -4.1823 | 2012-04-16 | 50.3373 | -4.274 | 262 | 7.28 | 3 |
| B0353 | Raja clavata | M | 2011-10-05 | 753 | 489 | 50.3627 | -4.1782 | 2012-07-28 | 50.3702 | -4.1319 | 280 | 3.39 | 2 |
| B0355 | Raja clavata | M | 2011-10-05 | 622 | 432 | 50.3627 | -4.1782 | 2012-07-28 | 50.3455 | -4.153 | 280 | 2.62 | 1 |
| B0387 | Raja clavata | M | 2012-03-21 | 592 | 408 | 50.3176 | -4.1811 | 2012-06-01 | 50.3445 | -4.2725 | 65 | 7.16 | 15 |
| B0391 | Raja clavata | M | 2012-03-21 | 705 | 466 | 50.3176 | -4.1811 | 2012-04-11 | -- | -- | 14 | -- | 17 |
| B0394 | Raja clavata | M | 2012-03-21 | 718 | 459 | 50.3176 | -4.1811 | 2012-04-11 | -- | -- | 14 | -- | 11 |
| A01709 | Raja microocellata | F | 2009-06-24 | 851 | 611 | 50.2955 | -4.1963 | 2010-05-24 | 50.2422 | -4.0646 | 333 | 11.09 | 2 |
| A01783 | Raja microocellata | F | 2010-01-14 | 621 | 454 | 50.3095 | -4.1908 | 2010-04-28 | 50.3204 | -4.241 | 102 | 3.76 | 12 |
| A01786 | Raja microocellata | F | 2010-01-14 | 581 | 430 | 50.3095 | -4.1908 | 2010-07-09 | 50.2632 | -3.8983 | 174 | 21.44 | 18 |
| A01787 | Raja microocellata | F | 2010-01-14 | 636 | 482 | 50.3095 | -4.1908 | 2010-04-23 | -- | -- | 97 | -- | 11 |
| A01789 | Raja microocellata | F | 2010-01-14 | 661 | 498 | 50.3095 | -4.1908 | 2010-04-29 | 50.0181 | -4.9638 | 103 | 63.96 | 7 |
| A01794 | Raja microocellata | M | 2010-01-14 | 650 | 464 | 50.3095 | -4.1908 | 2010-08-02 | 50.3288 | -4.2341 | 198 | 3.75 | 4 |
| A01795 | Raja microocellata | M | 2010-01-14 | 737 | 504 | 50.3095 | -4.1908 | 2010-04-10 | 50.3406 | -4.1617 | 84 | 4.03 | 24 |
| A01810 | Raja microocellata | M | 2010-02-18 | 774 | 518 | 50.3013 | -4.1067 | 2010-05-26 | -- | -- | 90 | -- | 23 |
| A01811 | Raja microocellata | F | 2010-02-18 | 648 | 470 | 50.3013 | -4.1067 | 2010-05-21 | 50.3413 | -4.1571 | 85 | 5.71 | 7 |
| A01813 | Raja microocellata | M | 2010-02-10 | 623 | 445 | 50.3013 | -4.1067 | 2010-03-10 | 50.2742 | -4.0652 | 13 | 4.22 | 5 |
| A05967 | Raja microocellata | F | 2010-12-07 | 540 | 411 | 50.3098 | -4.2104 | 2012-01-08 | -- | -- | 395 | -- | 2 |
| A05969 | Raja microocellata | M | 2011-01-18 | 800 | 546 | 50.3187 | -4.133 | 2011-01-21 | 50.2931 | -4.0417 | 1 | 7.09 | 1 |
| A05970 | Raja microocellata | M | 2011-01-18 | 730 | 516 | 50.3187 | -4.133 | 2011-09-01 | -- | -- | 224 | -- | 15 |

| <i>Tag</i> | <i>Species</i> | <i>Sex</i> | <i>Release Date</i> | <i>Length (mm)</i> | <i>Disk (mm)</i> | <i>Release Latitude</i> | <i>Release Longitude</i> | <i>Recapture Date</i> | <i>Recapture Latitude</i> | <i>Recapture Longitude</i> | <i>Days At Liberty</i> | <i>Displacement (km)</i> | <i>No of events</i> |
|------------|--------------------|------------|---------------------|--------------------|------------------|-------------------------|--------------------------|-----------------------|---------------------------|----------------------------|------------------------|--------------------------|---------------------|
| A05972 | Raja microocellata | M | 2011-01-18 | 697 | 491 | 50.3187 | -4.133 | 2011-05-05 | 50.2627 | -3.8832 | 105 | 18.83 | 6 |
| A05982 | Raja microocellata | F | 2010-04-12 | 475 | 346 | 50.3008 | -4.1165 | 2010-06-18 | 50.2458 | -4.7875 | 65 | 48.13 | 43 |
| A05984a | Raja microocellata | F | 2010-05-06 | 516 | 384 | 50.316 | -4.1721 | 2011-03-26 | 50.3504 | -4.3167 | 322 | 10.97 | 15 |
| A05990 | Raja microocellata | M | 2011-01-18 | 662 | 465 | 50.3187 | -4.133 | 2011-08-02 | 50.3333 | -4.2333 | 194 | 7.32 | 1 |
| A06016 | Raja microocellata | F | 2010-12-07 | 536 | 382 | 50.3098 | -4.2104 | 2011-07-11 | 50.3125 | -4.5845 | 214 | 26.60 | 1 |
| B0341 | Raja microocellata | F | 2011-07-14 | 610 | 452 | 50.3137 | -4.1789 | 2011-07-27 | 50.3054 | -4.4901 | 6 | 22.14 | 49 |
| B0360 | Raja microocellata | F | 2012-01-11 | 562 | 417 | 50.334 | -4.1635 | 2012-05-04 | -- | -- | 108 | -- | 1 |
| B0361 | Raja microocellata | F | 2012-01-11 | 617 | 452 | 50.334 | -4.1635 | 2012-12-10 | 50.2669 | -3.9026 | 328 | 20.00 | 3 |
| B0373 | Raja microocellata | M | 2012-01-11 | 584 | 428 | 50.334 | -4.1635 | 2013-02-23 | 50.2044 | -3.7599 | 403 | 32.14 | 2 |
| B0374 | Raja microocellata | M | 2012-01-11 | 616 | 442 | 50.334 | -4.1635 | 2012-04-11 | -- | -- | 85 | -- | 2 |
| B0405a | Raja microocellata | M | 2013-04-30 | 760 | 515 | 50.3175 | -4.1861 | 2013-06-02 | 50.3588 | -4.3231 | 17 | 10.76 | 2 |
| A01797 | Raja montagui | M | 2010-01-14 | 675 | 437 | 50.3095 | -4.1908 | 2011-04-26 | 50.3413 | -4.276 | 465 | 7.01 | 1 |
| A01805 | Raja montagui | F | 2010-01-28 | 708 | 479 | 50.2783 | -4.7677 | 2010-03-08 | 50.2742 | -4.0652 | 38 | 49.98 | 10 |
| A01806 | Raja montagui | F | 2010-01-28 | 747 | 489 | 50.2783 | -4.7677 | 2010-03-11 | 50.2753 | -4.0322 | 41 | 52.33 | 8 |
| A01837 | Raja montagui | M | 2010-04-07 | 666 | 406 | 50.302 | -4.1567 | 2010-06-02 | 50.258 | -3.9183 | 54 | 17.65 | 4 |
| A01837a | Raja montagui | M | 2010-06-02 | 667 | 408 | 50.2733 | -3.935 | 2011-04-10 | 50.2617 | -3.9167 | 304 | 1.84 | 2 |
| A05883 | Raja montagui | F | 2010-04-15 | 690 | 462 | 50.2597 | -4.0041 | 2010-07-08 | 50.2279 | -4.066 | 83 | 5.65 | 5 |
| A05887 | Raja montagui | M | 2010-04-15 | 654 | 411 | 50.2591 | -4.0203 | 2011-04-04 | -- | -- | 353 | -- | 1 |
| A05928 | Raja montagui | F | 2010-07-13 | 645 | 431 | 50.3175 | -4.1332 | 2012-04-29 | 50.253 | -3.9037 | 654 | 17.83 | 6 |
| A05983 | Raja montagui | F | 2010-04-15 | 552 | 360 | 50.2597 | -4.0041 | 2011-01-20 | 50.026 | -4.0624 | 279 | 26.34 | 7 |

Table S2: Datasets without selected central place events

| <i>Tag</i> | <i>Species</i> | <i>Sex</i> | <i>Release Date</i> | <i>Length (mm)</i> | <i>Disk (mm)</i> | <i>Release Latitude</i> | <i>Release Longitude</i> | <i>Recapture Date</i> | <i>Recapture Latitude</i> | <i>Recapture Longitude</i> | <i>Days At Liberty</i> | <i>Displacement (km)</i> |
|------------|----------------|------------|---------------------|--------------------|------------------|-------------------------|--------------------------|-----------------------|---------------------------|----------------------------|------------------------|--------------------------|
| A05885 | Raja brachyura | F | 2010-04-15 | 621 | 448 | 50.2597 | -4.0041 | 2010-04-25 | 50.2466 | -4.0645 | 9 | 4.54 |
| A01711 | Raja clavata | F | 2009-09-04 | 849 | 573 | 50.3334 | -4.1959 | 2009-10-02 | 50.3338 | -4.1897 | 25 | 0.00 |
| A01772 | Raja clavata | F | 2006-10-14 | 875 | 584 | 50.3479 | -4.1501 | 2010-05-07 | 50.3281 | -4.1912 | 154 | 3.66 |
| A01798 | Raja clavata | F | 2010-01-15 | 861 | 598 | 50.3292 | -4.1655 | 2010-05-15 | 50.3296 | -4.1923 | 114 | 1.91 |
| A01799 | Raja clavata | F | 2010-01-15 | 865 | 604 | 50.3292 | -4.1655 | 2010-02-11 | -- | -- | 21 | -- |
| A05952 | Raja clavata | F | 2010-10-06 | 830 | 596 | 50.3187 | -4.1365 | 2011-01-26 | -- | -- | 110 | -- |
| A06000 | Raja clavata | F | 2010-06-09 | 558 | 410 | 50.3307 | -4.1336 | 2010-07-25 | -- | -- | 44 | -- |
| A06026 | Raja clavata | M | 2010-11-03 | 494 | 345 | 50.3621 | -4.1905 | 2010-12-16 | -- | -- | 41 | -- |
| B0357 | Raja clavata | F | 2011-10-05 | 736 | 511 | 50.3215 | -4.1346 | 2011-12-21 | -- | -- | 13 | -- |
| B0374a | Raja clavata | F | 2012-06-26 | 805 | 555 | 50.2987 | -4.1868 | 2012-10-07 | 50.3259 | -4.2368 | 96 | 4.67 |
| B0385 | Raja clavata | M | 2012-03-21 | 709 | 469 | 50.3176 | -4.1811 | 2012-04-28 | -- | -- | 31 | -- |
| B0386 | Raja clavata | M | 2012-03-21 | 709 | 478 | 50.3176 | -4.1811 | 2012-05-08 | -- | -- | 41 | -- |
| B0389 | Raja clavata | M | 2012-03-21 | 810 | 495 | 50.3176 | -4.1811 | 2012-04-02 | -- | -- | 5 | -- |
| A01866 | Raja montagui | F | 2010-04-15 | 635 | 442 | 50.2601 | -3.9339 | 2010-06-02 | 50.258 | -3.9183 | 47 | 1.13 |

Supplementary plots



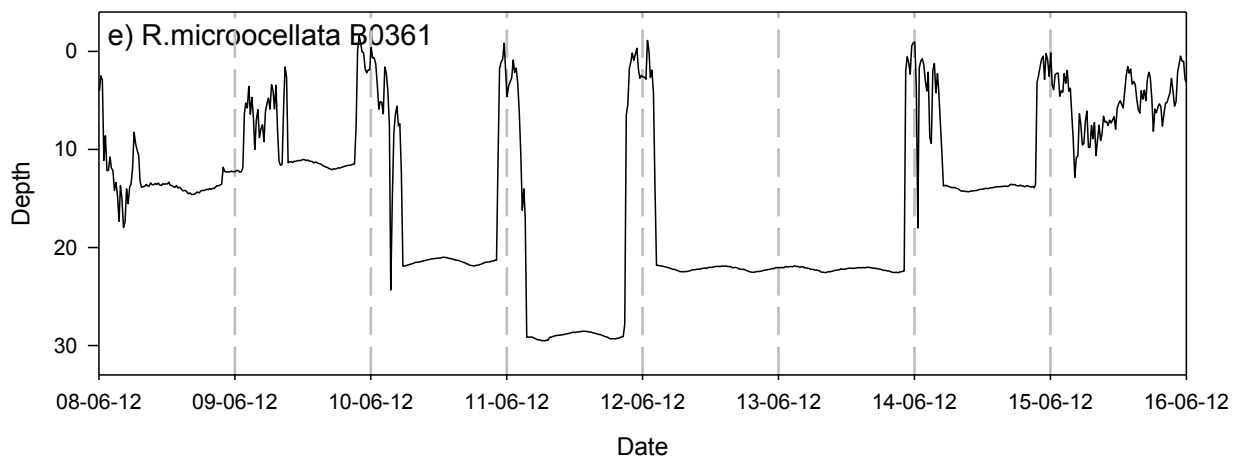
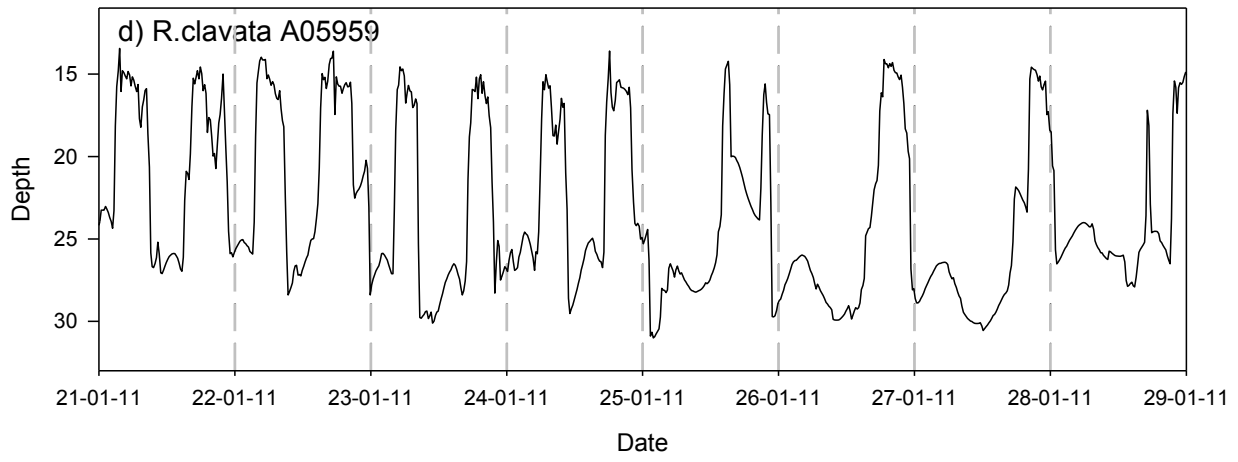


Figure S1: Example DVM plots

Supplementary analysis

Selection of events for analysis

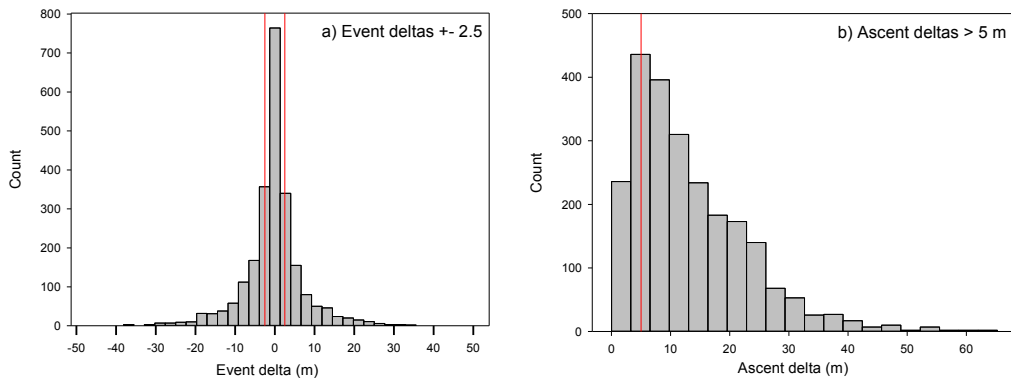


Figure S2: Histograms of event and ascent deltas

The histograms show the range of event (a) and ascent (b) deltas observed in the recorded events. Red lines indicate the cut off values for the events selected for analysis in this paper, where the vertical movement exceeds 5 m, yet the animal returns to within 2.5 m of the starting depth.

Software used to identify event times

To aid in the identification of DVM events, software was developed to display a depth time-series with the option of 1 in 10 under-sampling in order to fit more of the time-series on the display. A sequence of four mouse clicks was used to mark the four defining times of an event (event start, plateau start, plateau end, event end) as shown in the main text (figure 1). Once the final event time had been marked the four times were written to a table in Microsoft Access™ database. When all events for a time-series had been identified in this way the program then processed the non under-sampled time-series data to compute the range of metrics required for the analysis of the events: ascent/descent deltas (overall vertical displacements), speeds and durations; plateau delta, duration and activity (sum of and mean vertical displacements) and pre-event activity (activity in the hour prior to the event start). In addition a straightness index (SI) for each phase was calculated using L_0/L_1 where L_0 is the delta and L_1 is the sum of step lengths. The SI therefore gives a value in the range 0-1, where 1 represents a direct movement and lower values represent reduced straightness, or increased tortuosity.

Event frequency by length

Because of the tagging protocol employed, all individuals were mature and therefore the range of lengths was limited to between 475 and 884 mm. It was not possible therefore to investigate ontogenetic changes in the occurrence of DVM events. Within the range of lengths available no significant relationship was found between length and event frequency (Figure S3; *R. brachyura* $r^2=0.04$, $p=0.53$; *R. clavata* $r^2=0.03$, $p=0.78$; *R. microocellata* $r^2=0.02$, $p=0.51$; *R. montagui* $r^2=0.05$, $p=0.56$; SigmaPlot linear regression).

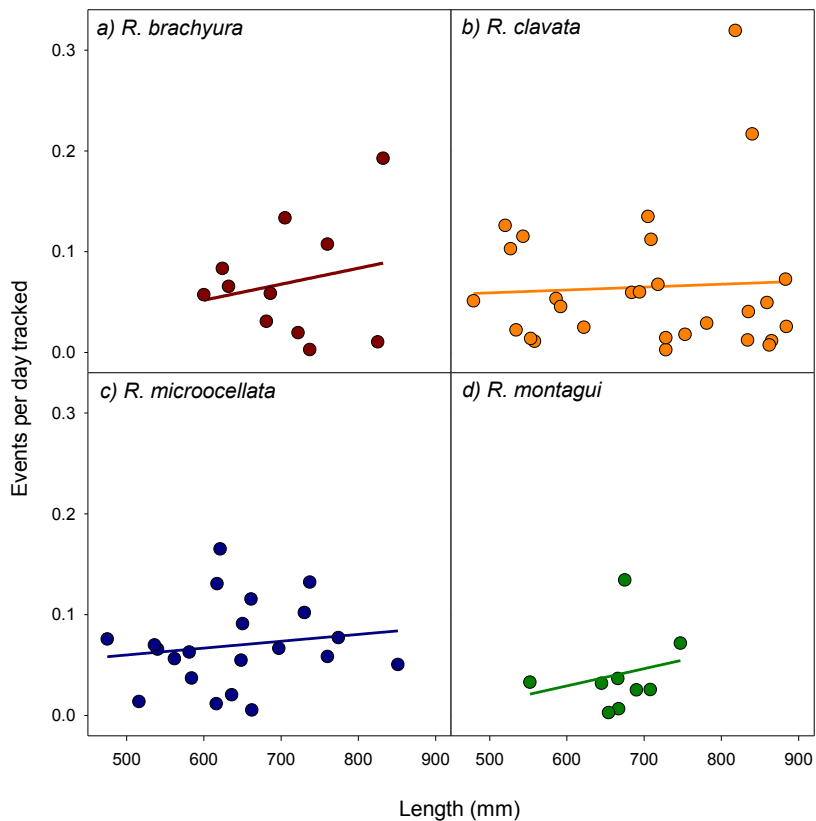


Figure S3: Length v event frequency

The sporadic nature of the observed DVM

The DVM events observed differ from the regular diel vertical migrations seen in many pelagic predators by being relatively infrequent and highly variable in nature. For this reason methods typically associated with the analysis of time-series were not considered appropriate. To support this assertion we performed a spectral analysis of our depth time-series data using FFT and then analysed the results to identify the 1 cycle per day peaks indicative of DVM behaviour. If the observed DVM represented a rhythmic behaviour then there should be a correlation between the amplitude of the 1 cycle/day spectral signal and the number of events observed. This was found not to be the case. The results are given in and are shown as a scatter plot in Figure S4. Linear regression gives an r^2 value of only 0.127. Figure S5 shows example spectral plots and illustrates that the amplitude of the 1 cycle/day signal is not a consistent indicator of the number of DVM events found.

Table S3: Amplitude of FFT 1 cycle/day peak v no of events

The table shows, for each individual, the number of recorded events and the relative amplitude of the spectral peak at 1 cycle/day indicative of DVM behaviour. Where this amplitude is greater than 10% of the highest spectral peak in that track it is deemed to be a clear signal of DVM.

| <i>Species</i> | <i>Track</i> | <i>No of events</i> | <i>Max peak fft</i> | <i>Clear DVM peak?</i> |
|--------------------|--------------|---------------------|---------------------|------------------------|
| Raja brachyura | A01775.nc | 4 | 2.98% | |
| Raja brachyura | A01840.nc | 2 | 5.74% | |
| Raja brachyura | A01846.nc | 5 | 25.27% | Y |
| Raja brachyura | A01852.nc | 1 | 4.56% | |
| Raja brachyura | A05886.nc | 6 | 35.90% | Y |
| Raja brachyura | A05908.nc | 7 | 32.15% | Y |
| Raja brachyura | A05927.nc | 2 | 24.43% | Y |
| Raja brachyura | A05950.nc | 1 | 3.31% | |
| Raja brachyura | A05962.nc | 28 | 100.00% | Y |
| Raja brachyura | A06014.nc | 4 | 13.27% | Y |
| Raja brachyura | B0357a.nc | 2 | 3.54% | |
| Raja clavata | A01711a.nc | 3 | 19.08% | Y |
| Raja clavata | A01736.nc | 46 | 13.91% | Y |
| Raja clavata | A01764.nc | 13 | 43.92% | Y |
| Raja clavata | A01767.nc | 31 | 19.23% | Y |
| Raja clavata | A01770.nc | 3 | 16.86% | Y |
| Raja clavata | A01770a.nc | 12 | 26.27% | Y |
| Raja clavata | A01773.nc | 2 | 100.00% | Y |
| Raja clavata | A05888.nc | 1 | 100.00% | Y |
| Raja clavata | A05959.nc | 26 | 19.41% | Y |
| Raja clavata | A05961.nc | 1 | 30.57% | Y |
| Raja clavata | A05984.nc | 2 | 92.28% | Y |
| Raja clavata | A06001.nc | 1 | 7.61% | |
| Raja clavata | A06015.nc | 4 | 3.60% | |
| Raja clavata | B0324.nc | 15 | 100.00% | Y |
| Raja clavata | B0334.nc | 23 | 100.00% | Y |
| Raja clavata | B0336.nc | 47 | 100.00% | Y |
| Raja clavata | B0340.nc | 1 | 4.51% | |
| Raja clavata | B0342.nc | 15 | 39.74% | Y |
| Raja clavata | B0343.nc | 1 | 27.36% | Y |
| Raja clavata | B0344.nc | 4 | 29.69% | Y |
| Raja clavata | B0345.nc | 2 | 5.26% | |
| Raja clavata | B0347.nc | 10 | 9.30% | |
| Raja clavata | B0348.nc | 13 | 100.00% | Y |
| Raja clavata | B0353.nc | 5 | 100.00% | Y |
| Raja clavata | B0355.nc | 7 | 23.08% | Y |
| Raja clavata | B0387.nc | 3 | 100.00% | Y |
| Raja clavata | B0391.nc | 2 | 27.02% | Y |
| Raja clavata | B0394.nc | 1 | 1.55% | |
| Raja microocellata | A01709.nc | 15 | 33.58% | Y |
| Raja microocellata | A01783.nc | 17 | 75.25% | Y |
| Raja microocellata | A01786.nc | 11 | 15.75% | Y |
| Raja microocellata | A01787.nc | 2 | 10.08% | Y |
| Raja microocellata | A01789.nc | 12 | 43.48% | Y |
| Raja microocellata | A01794.nc | 18 | 49.93% | Y |
| Raja microocellata | A01795.nc | 11 | 38.97% | Y |

| <i>Species</i> | <i>Track</i> | <i>No of events</i> | <i>Max peak fft</i> | <i>Clear DVM peak?</i> |
|--------------------|--------------|---------------------|---------------------|------------------------|
| Raja microocellata | A01810.nc | 7 | 5.50% | |
| Raja microocellata | A01811.nc | 4 | 29.33% | Y |
| Raja microocellata | A05967.nc | 24 | 47.76% | Y |
| Raja microocellata | A05970.nc | 23 | 30.95% | Y |
| Raja microocellata | A05972.nc | 7 | 10.43% | Y |
| Raja microocellata | A05982.nc | 5 | 100.00% | Y |
| Raja microocellata | A05984a.nc | 2 | 92.00% | Y |
| Raja microocellata | A05990.nc | 1 | 27.02% | Y |
| Raja microocellata | A06016.nc | 15 | 74.14% | Y |
| Raja microocellata | B0360.nc | 6 | 25.12% | Y |
| Raja microocellata | B0361.nc | 43 | 52.01% | Y |
| Raja microocellata | B0373.nc | 15 | 100.00% | Y |
| Raja microocellata | B0374.nc | 1 | 7.72% | |
| Raja microocellata | B0405a.nc | 1 | 1.56% | |
| Raja montagui | A01797.nc | 49 | 100.00% | Y |
| Raja montagui | A01805.nc | 1 | 4.27% | |
| Raja montagui | A01806.nc | 3 | 4.03% | |
| Raja montagui | A01837.nc | 2 | 4.45% | |
| Raja montagui | A01837a.nc | 2 | 2.13% | |
| Raja montagui | A05883.nc | 2 | 2.23% | |
| Raja montagui | A05887.nc | 1 | 4.18% | |
| Raja montagui | A05928.nc | 10 | 3.28% | |
| Raja montagui | A05983.nc | 8 | 91.35% | Y |
| Raja montagui | A05983.nc | 8 | 70.52% | Y |

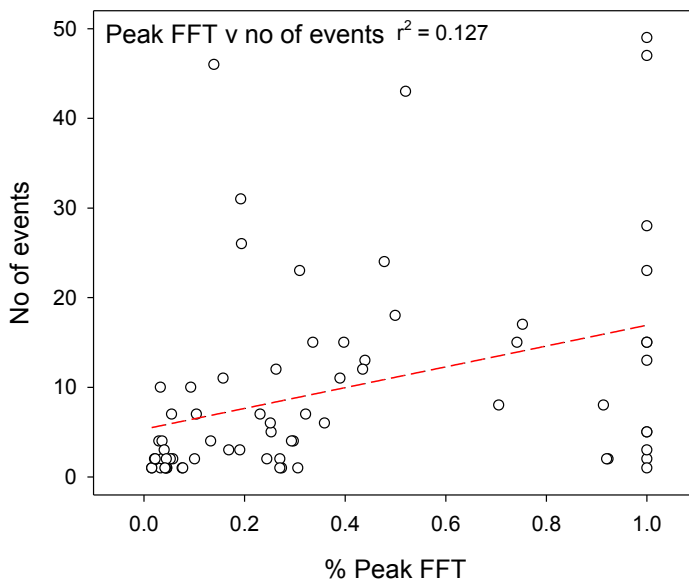


Figure S4: Amplitude of 1 cycle/day spectral signal v no of observed events

The amplitude of the 1 cycle/day spectral signal is not significantly correlated with the number of observed DVM events, as would be expected if DVM events were consistent.

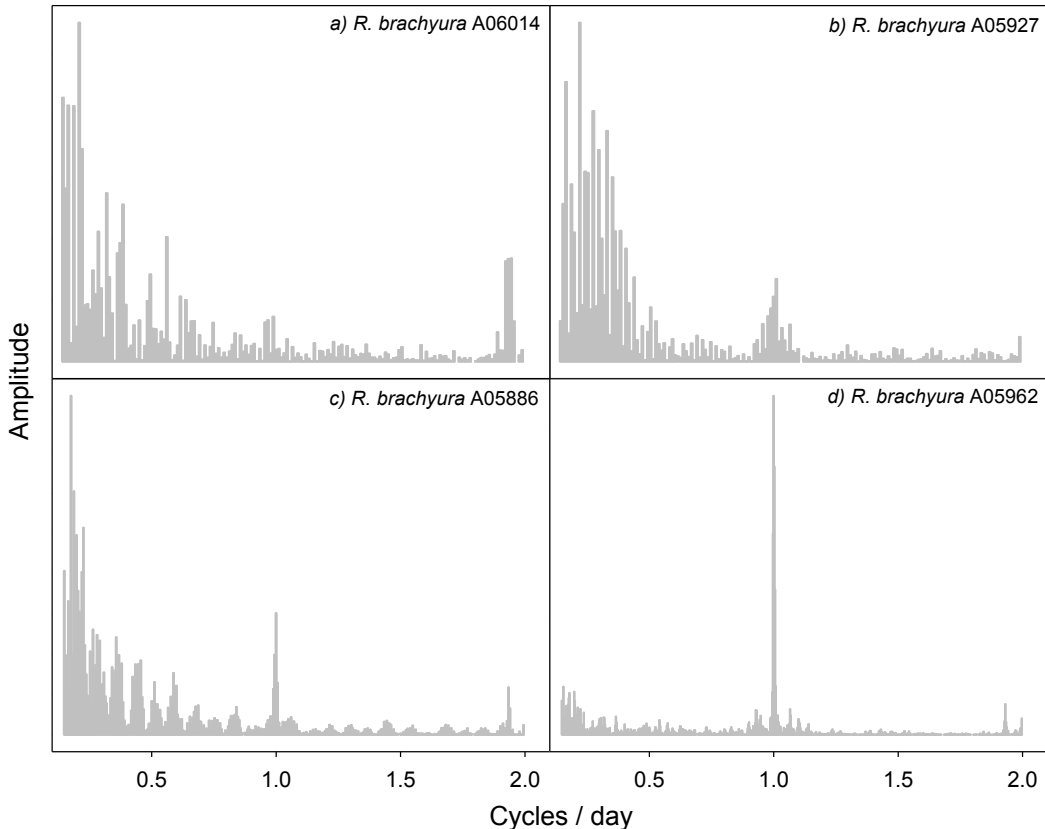


Figure S5 Example spectral plots

These plots show the spectral analysis of four tracks and illustrate an increasing component of a 1 cycle / day signal. The amplitude of this signal is not well correlated with the number of DVM events found. In this case, although d) has the largest number of events (28) a) has more events (4) than b) (2).

Continuous wavelet analysis

A further possibility for the analysis of regular events in time-series data is wavelet analysis (e.g. Giacalone et al. 2015, Zhang et al. 2017). While the Fourier Transform transforms a time-series from the time domain to the frequency domain, to produce a frequency / amplitude (or spectral) plot, a wavelet transform transforms a time-series into a time / frequency plot. Wavelet analysis can therefore be used to investigate how the frequency composition of a time-series changes over time. In particular, wavelet transforms are useful in the study of non-stationary waveforms, where the amplitude of the component frequencies varies over time, as is often the case with complex biological signals. To determine its usefulness here, a sample track (*R. brachyura* A05962) was first interpolated from 20 s and 2 minute intervals to 5 minute intervals. The R package *WaveletComp* (Roesch and Schmidbauer 2014) was used to analyse the interpolated time-series using the command:

```
w = analyze.wavelet(mydata, "mydata.Depth",loess.span=0,dt=1,
  dj=1/32,lowerPeriod=32,upperPeriod=2048,make.pval = T, n.sim = 10)
```

The period parameters set the lower frequency bound to 2.66 h and the upper to 170 h, to ensure that frequencies of 0.5 to 1 cycle per day are adequately captured ((32*5)/60 mins and (2048*5)/60 mins). The results of the analysis are shown in a wavelet power spectrum (Figure S6) and it can be seen that there are a group of peaks of 1 cycle per day activity from approximately mid-April to late July. Earlier in the year there is a series of peaks of activity with a period of approximately 144, equivalent to 2 cycles per day, which indicate the tidal cycle. The average wavelet power, which

shows the summarised amplitude of each frequency, shows a clear peak at a period of 288, with a smaller peak at approximately 144; these peaks correspond to 1 cycle/day (DVM) and ~ 2 cycles/day (tidal) signals respectively Figure S7. The plotted depth time series in Figure S6 matches well with the occurrence of peaks in the wavelet power spectrum.

However, while the analysis does confirm that 1 cycle/day activity is occurring and shows the time of year when this is most common, and does identify when DVM is more likely, the output is largely descriptive and is not capable of providing the rich quantitative data that the manual approach of marking the events individually yields. Therefore, whilst the manual method employed here to identify DVM events is laborious it does provide detailed information relating to the times and distances involved in every DVM event, which wavelet analysis cannot provide.

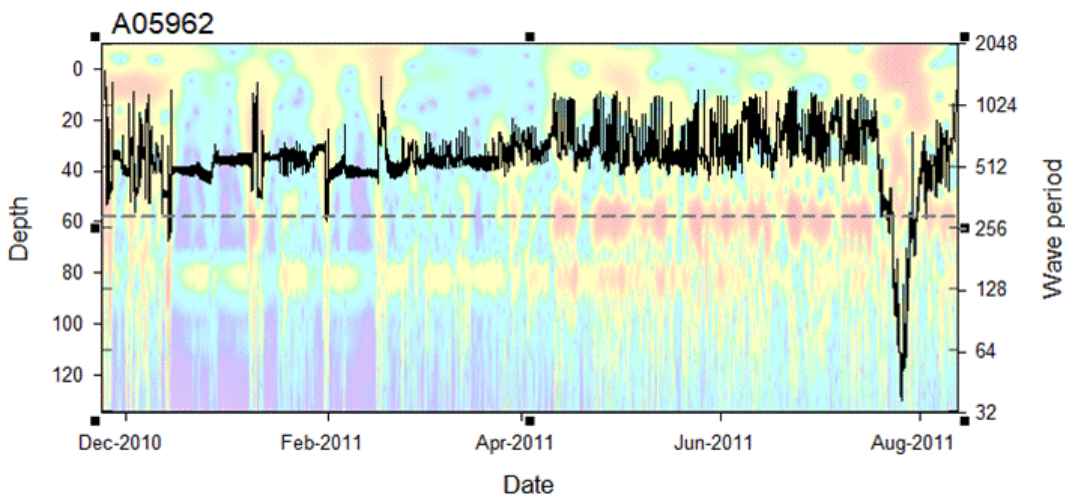


Figure S6: Wavelet analysis of *R. brachyura* A05962

The plot shows the depth time-series for A05962 (interpolated to 5 minutes) overlaid on the wavelet power spectrum. The grey dashed horizontal line is at a period of 288 (1 cycle per day) and represent the frequency of DVM events.

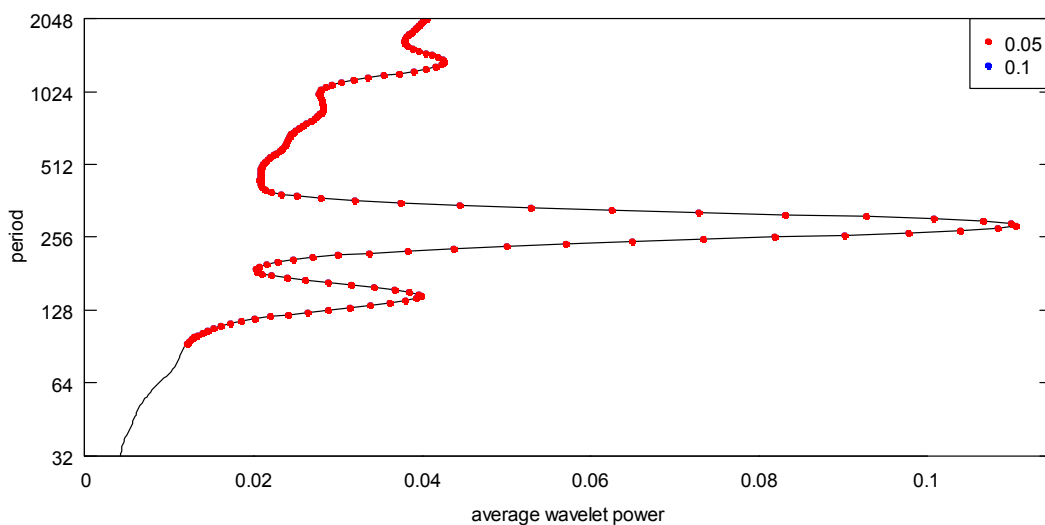


Figure S7: Average power plot

The plot shows a clear peak at a period of approximately 288, the signal of DVM.

Natural habitat heterogeneity

The area where tagged animals were tracked comprises a heterogeneous mosaic of habitats when characterised in terms of water depth, substratum type, water column environmental gradients and temporal scales of fluctuations in those gradients. The study area was located in the coastal waters of the western English Channel, from the city of Plymouth foreshore to approximately 40 km offshore, and spanning from Dodman Point (southeast Cornwall) in the west to Torbay (south Devon) in the east (see Figure S8). Water depth generally increases with distance from the shore, to a maximum depth of 76.5 m approximately 38 km due south of Par Sands (SE Cornwall), although the seabed shelves to 60 m more steeply in the eastern part of the study area (south of Start Point, S. Devon) (Figure S8a). Shallow rocky outcrops are found at the tidally exposed Eddystone Rocks which lie 18 km due south of Whitsand Bay, SE Cornwall and WNW of these rocks at Hand Deeps (min. depth, 7m). A further shallow rocky area known as the East Rutts (min. depth, 8 m) lies approximately 8 km WSW of Bolt Tail.

Seabed substrates within the study site have been mapped by UKSeaMap 2010 (McBreen et al. 2011). This project derived an interactive map of broad scale predicted seabed habitat for the UK continental shelf, combining existing substrate data from a variety of sources to map the seabed substrates over the entire UK continental shelf (Figure S8b). Substrate type varies considerably throughout the study site from bedrock and the rocky outcrops mentioned above, through mixed sediments and sands to fine mud. This degree of variation in substrate type is supported by descriptions of the main collecting grounds in the study area in the Plymouth Marine Fauna (MBA 1957), which also describes other notable habitats including seagrass beds and both natural and artificial reefs, in the form of sea defences and shipwrecks. However, from the descriptions in this document it is also clear that there is also a large amount of variability even within these more general categories. For example, rock may be exposed to high levels of wave action and therefore be barren, it may be covered in encrusting faunal communities such as hydroids, ascidians and anemones, or, in more sheltered locations, it may provide a suitable substrate for the settlement of large kelps. Naturally, the fauna of these habitats also vary. Wave exposed and mobile sediments will likely be relatively barren. Immobile and burrowing species will have specific habitat requirements relating to sediment grain size and prey availability, and even relatively mobile species such as fish, cephalopods and crustaceans will exhibit habitat preferences. Thus, the study area supports heterogeneous habitats as measured by surveys spanning the last century and in terms of substratum type and the species that inhabit those seabed areas.

The water column above the seabed in this area is also variable. The western English Channel is a highly dynamic region with significant physical and biogeographical boundaries (Southward et al. 2005). For example, the area offshore of Plymouth is where the Ushant front, a seasonally persistent thermal tidal front, reaches its northern extent. This front is not only characterised by strong horizontal and vertical gradients in water temperature and other physical characteristics, it is also a hydrographic feature with high productivity, having high in situ primary growth and physical aggregation of phytoplankton and zooplankton assemblages (Le Fèvre 1986). This highly dynamic water column confers heterogeneity to the underlying benthos through stronger physical gradients and nutrient pulses in addition to direct input of particulate carbon which influences community structure and functioning (Southward et al. 2005). These general features are exemplified in example maps. For instance, a map of mean summer (June – Aug 2009) sea-surface temperature values from satellite-derived sea surface temperature data available from the Medspiration project (<http://projets.ifremer.fr/cersat/Information/Projects/MEDSPIRATION2>) shows that whilst there is a general pattern of cooler water inshore, temperature values do not typically reflect the underlying bathymetric variation. There exists a stretch of cooler water (16.8 – 17.0°C) running SE from Start Point and water temperatures generally appear to increase with distance east or west of this line, to a maximum temperature of 18.4°C approximately 25 km due S of Fowey, SE Cornwall. Furthermore, figure S1d shows satellite-derived interannual variability in summer (June – August 1998 to 2008) front occurrence within the study site (Miller et al. 2010, Miller and Christodoulou 2014). Whilst it

is not possible to detect oceanic fronts reliably from the satellite in the few kilometres immediately adjacent to the coastline, variability in front occurrence fluctuates widely across the rest of the study area, with values ranging from 0 to 48 %. Even between adjacent locations, variability ranges widely, the result being that it is difficult to draw contours around areas with similar variability values. An exception to this is the area running roughly NW to SE and lying 10 – 20 km offshore from Bolt Head. This area corresponds to the site of a frequent summer front (Miller et al. 2010) and thus experiences lower levels of inter-annual variability in summer front occurrence (typically 0 – 16 %) than other regions of the study area (typically 20 – 40 %). This area lies on the SW extremity of the low SST area previously identified. However, areas of high front variability are also associated with this cool area (for example, the area of high variability 5 km south of Bolt Head). Thus, there are no obvious patterns relating variability in frontal occurrence to bathymetry, habitat type or sea surface temperature.

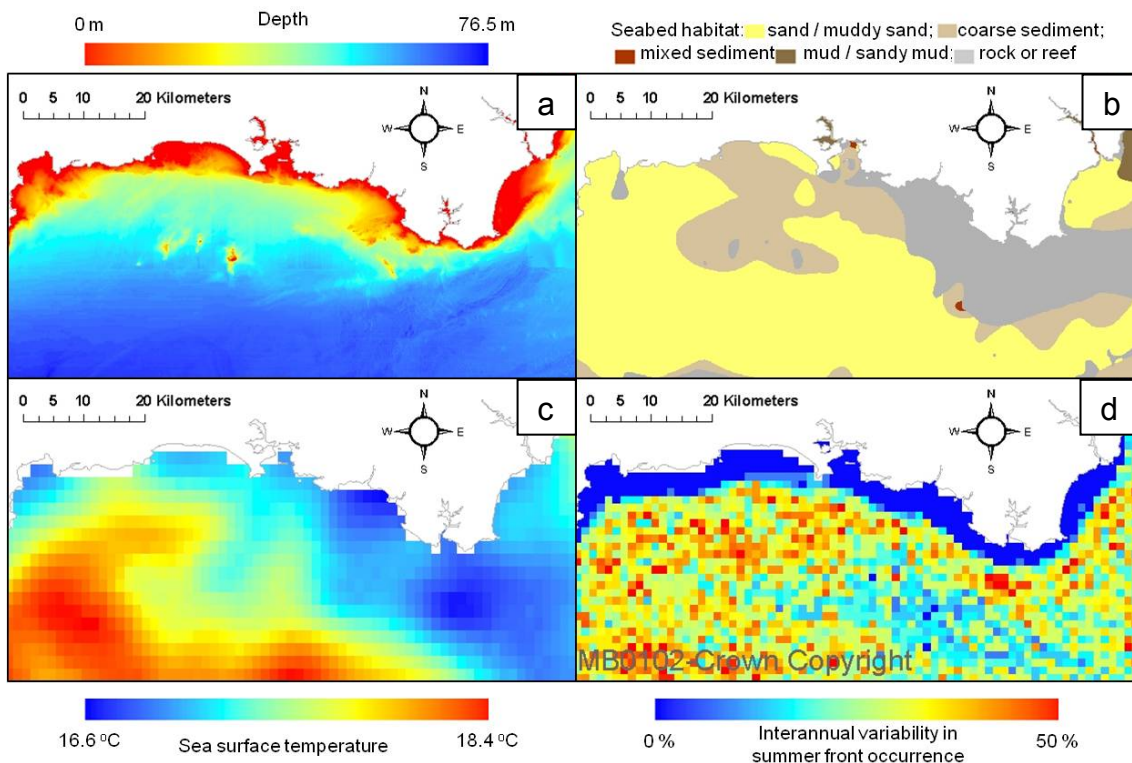


Figure S8: The coastal region of the western English Channel where animals were tracked is highly heterogeneous. (a) Seabed depth ranges from 0 to 76.5 m (© Crown Copyright/SeaZone Solutions. All Rights Reserved. Licence No. 052006.001 31st July 2011) and across this range of depths, seabed sediment type varies from sand, through mud, coarse and mixed sediments, to rock (b) (UKSeaMap 2010). The pelagic marine environment is also variable with the region being characterised by frontal, transitional waters seasonally and mean summer sea surface temperatures ranging from 16.6 – 18.4 °C (c) together with high levels of interannual variability (0 – 50 %) in the occurrence of fronts during summer months (d) (MB0102-Crown Copyright).

References

- Giacalone, V. M., A. Barausse, M. Gristina, C. Pipitone, V. Visconti, F. Badalamenti, and G. D'Anna. 2015. Diel activity and short-distance movement pattern of the European spiny lobster, *Palinurus elephas*, acoustically tracked. *Marine Ecology-an Evolutionary Perspective* 36:389-399.
- Le Fèvre, J. 1986. Aspects of the Biology of Frontal Systems. *Advances in Marine Biology* 23:163-299.
- MBA. 1957. Plymouth Marine Fauna Marine Biological Association of the United Kingdom, Plymouth, UK.
- McBreen, F., N. Askew, A. Cameron, D. Connor, H. Ellwood, and A. Carter. 2011. UK SeaMap 2010 Predictive mapping of seabed habitats in UK waters. 466, JNCC.
- Miller, P. I. and S. Christodoulou. 2014. Frequent locations of oceanic fronts as an indicator of pelagic diversity: Application to marine protected areas and renewables. *Marine Policy* 45:318-329.
- Miller, P. I., S. Christodoulou, and S. S. Picart. 2010. Accessing and developing the required biophysical datasets and data layers for Marine Protected Areas network planning and wider marine spatial planning purposes.
- Roesch, A. and H. Schmidbauer. 2014. WaveletComp: Computational Wavelet Analysis. R package version 1.0.
- Southward, A. J., O. Langmead, N. J. Hardman-Mountford, J. Aiken, G. T. Boalch, P. R. Dando, M. J. Genner, I. Joint, M. A. Kendall, N. C. Halliday, R. P. Harris, R. Leaper, N. Mieszkowska, R. D. Pingree, A. J. Richardson, D. W. Sims, T. Smith, A. W. Walne, and S. J. Hawkins. 2005. Long-term oceanographic and ecological research in the western English Channel. Pages 1-105 *Advances in Marine Biology*, Vol 47.
- Zhang, J. D., V. Hull, Z. Y. Ouyang, L. He, T. Connor, H. B. Yang, J. Y. Huang, S. Q. Zhou, Z. J. Zhang, C. Q. Zhou, H. M. Zhang, and J. G. Liu. 2017. Modeling activity patterns of wildlife using time-series analysis. *Ecology and Evolution* 7:2575-2584.