Supplementary Materials

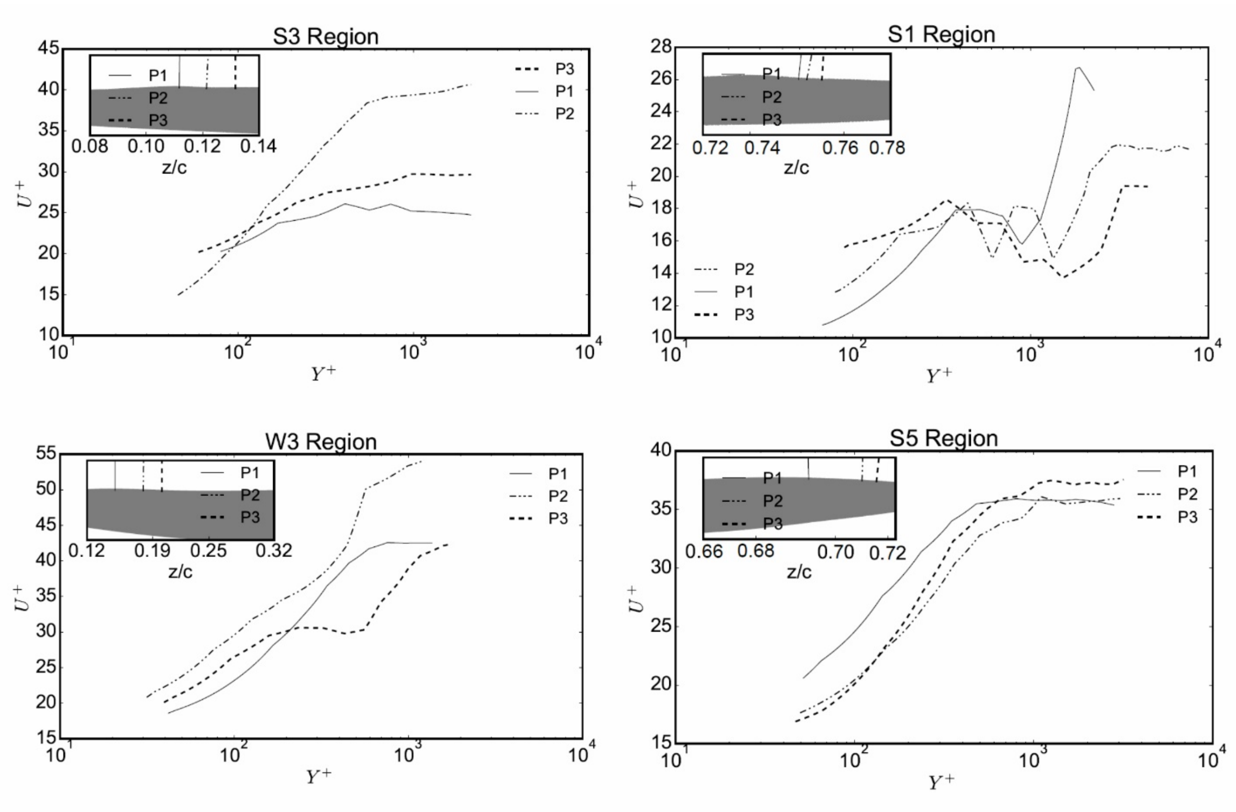


Fig. S1.

Streamwise velocity profiles plotted in wall units (i.e., U+ vs. Y+) determined on the whale surface along three vertical wall-normal lines originating at points P1, P2, P3 downstream of the whale's blowhole (top left; S3), downstream of the dorsal fin (top right; S1), by the flank behind the blowhole (bottom left; W3) and by the ridge anterior to the dorsal fin (bottom right; S5)); *z* is distance from leading edge, *c* is body length.

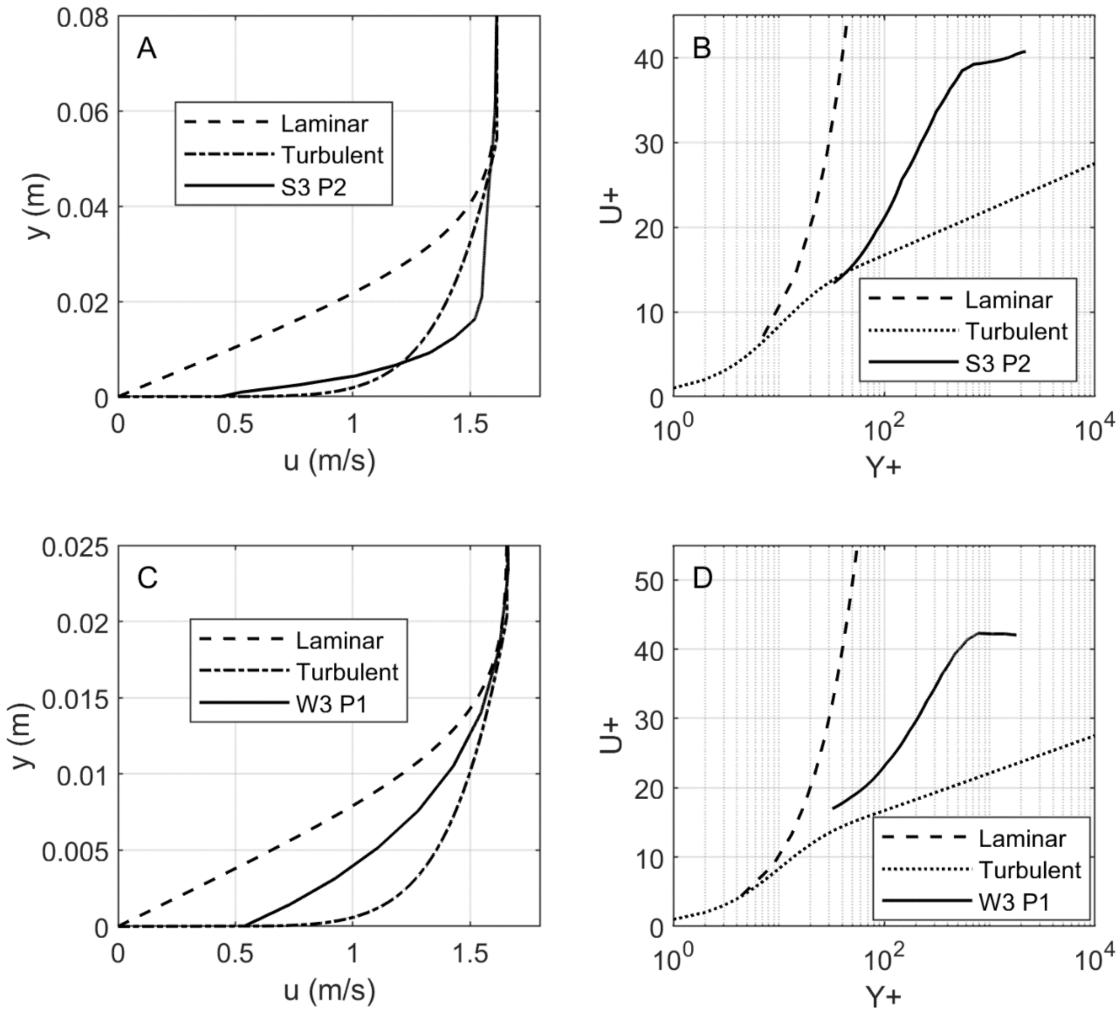


Fig. S2.

Two sample whale boundary layer profiles (solid lines) from Figs. 5 and S1 plotted in SI units and wall units with laminar and turbulent boundary layer profiles from flat plate theory. (A) and (B) show profile P2 from region S3, and (C) and (D) profile P1 from region W3. The plots give evidence of the transitional nature of the boundary layer: the whale profiles in (A) and (C) are suggestive of velocity gradients intermediate to laminar and turbulent; and in wall units, (B) and (D), they clearly fall between laminar and turbulent theory.

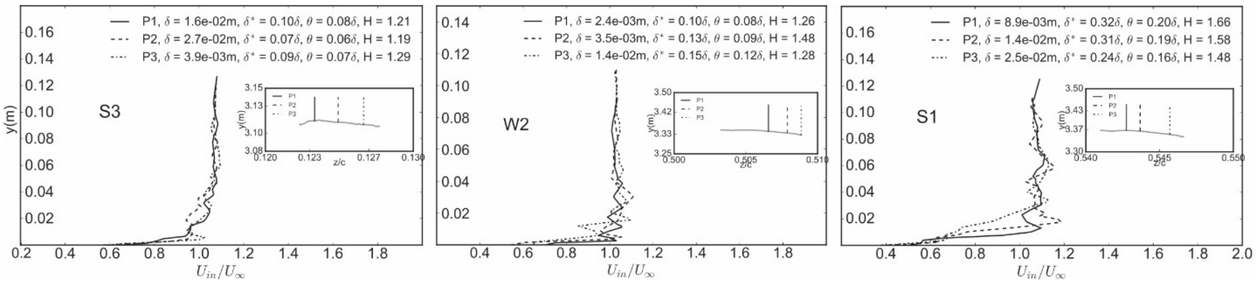


Fig. S3.

Instantaneous streamwise velocity profiles and boundary layer thicknesses at blowhole (S3), dorsal fin (S1), and flank beside dorsal fin (W2) used in computational fluid dynamic analyses of remora position (Fig. 5).

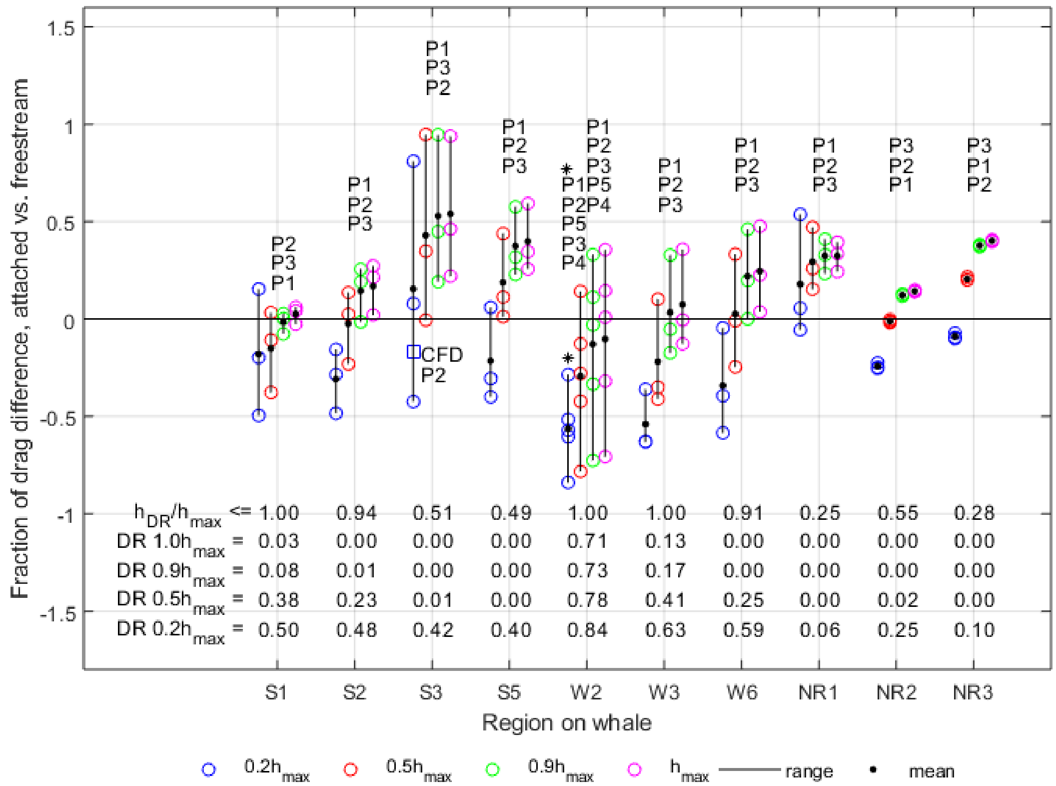


Fig. S4.
Fraction of the difference in drag between the attached state and coasting in the freestream (Eq. 11) for remora at various named profiles (e.g., P2) and regions on a blue whale. Negative values indicate that remora experience drag reduction in the attached state compared to freestream. Regions of separation (S), wakes (W), and few to no remora (NR) are presented. Data point colors indicate the height of modeled remora (blue shortest, pink tallest), and each data point is the fraction of drag difference at a specific region and profile (e.g., W2 P4), as referenced throughout this work. The black lines simply indicate range, and solid black points are mean values. The labels P1, P2, etc. above the data are in the same vertical order as each vertical group of data points so the drag difference for each named profile in this work can be read from the plot. As blue data points represent the smallest remora modeled ($h = 0.2h_{max}$), they are more likely to be below 0, indicating reduced drag in attachment. By contrast, pink data points, indicating the largest remora modeled ($h = h_{max}$), are less often below 0. The first row of the table on this figure lists the relative fish height below which drag reduction is available (h_{DR}/h_{max}) somewhere in the given region (column). Fish taller than this do not experience drag reduction in attachment in that region. The next rows of the table list the best drag difference offered (reductions only) in attachment for each modeled fish height at the given region (i.e., the absolute value of the lowest data point for each color). E.g., “DR $0.2h_{max}$” means “the drag fraction (reductions only) available in the given region for an attached remora $0.2h_{max}$ in height.” The case of drag reduction calculated by CFD at S3 P2--separation region 1, profile 2--is shown as a blue square. Note that greater drag reduction is available to a greater range of fish sizes in W and S regions, where fish were observed to localize, than in NR regions.

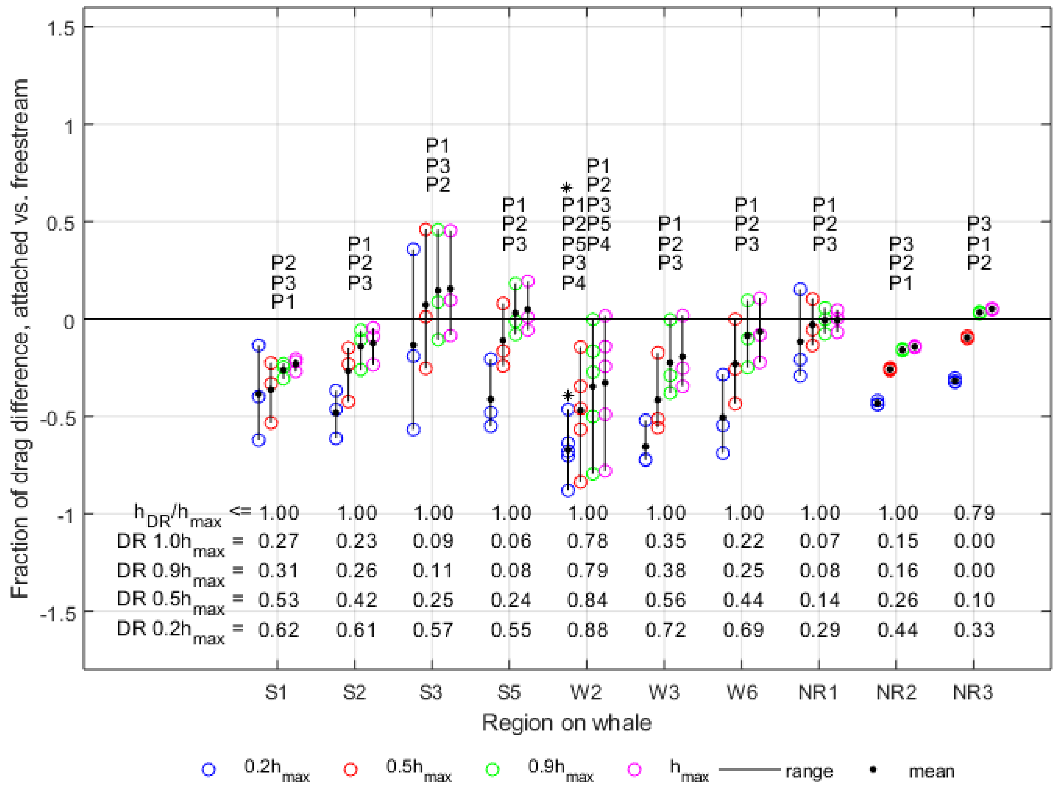


Fig. S5.
Fraction of the difference in drag between the attached state and coasting in the freestream for remora (Eq. 11) using a higher freestream drag coefficient, C_{DFS}, of 0.04 rather than the more conservative value of 0.03 used in the results shown in Fig. S5. In this case, drag reduction is available to fish of all sizes (data point color) in some parts of each region except in NR3. See the legend of Fig. S5 for a detailed explanation of the symbols and table in this figure.

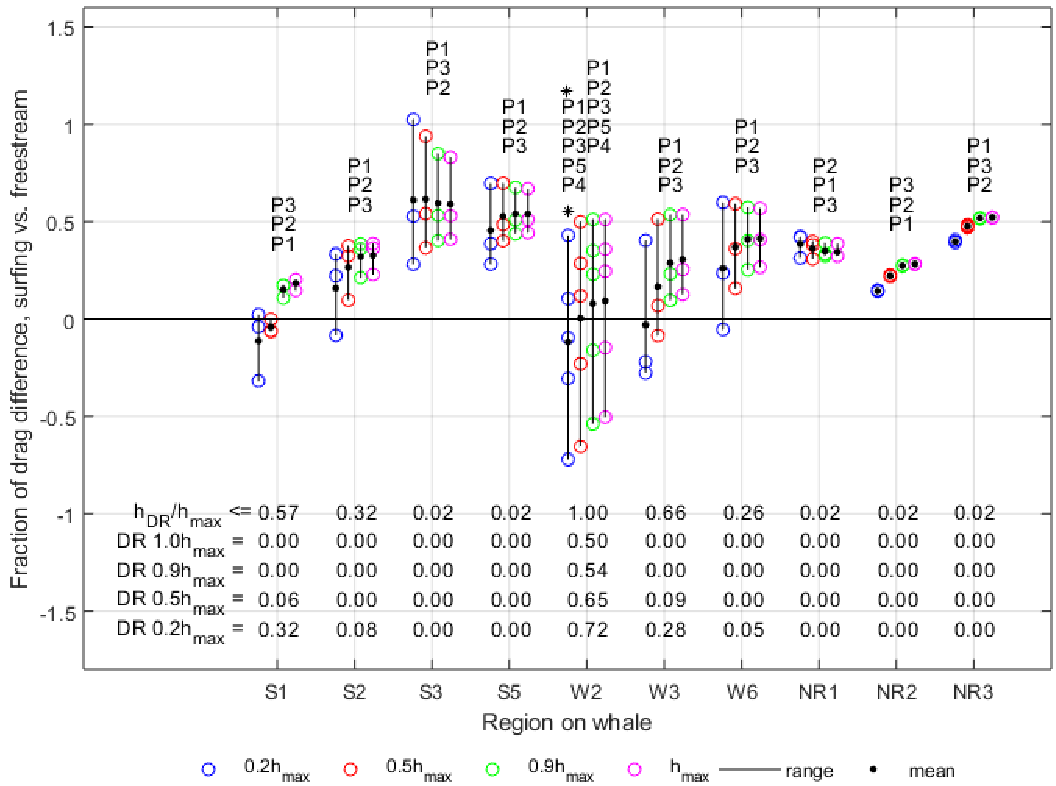


Fig. S6.
Fraction of the difference in drag between skimming at 1 cm off the whale surface and coasting in the freestream (where D_{BL} in Eq. 11 is the drag during skimming) for remora at various regions on a blue whale. Drag reduction is available for some remora sizes at some W and S regions. See the legend of Fig. S5 for a detailed explanation of the symbols and table in this figure.

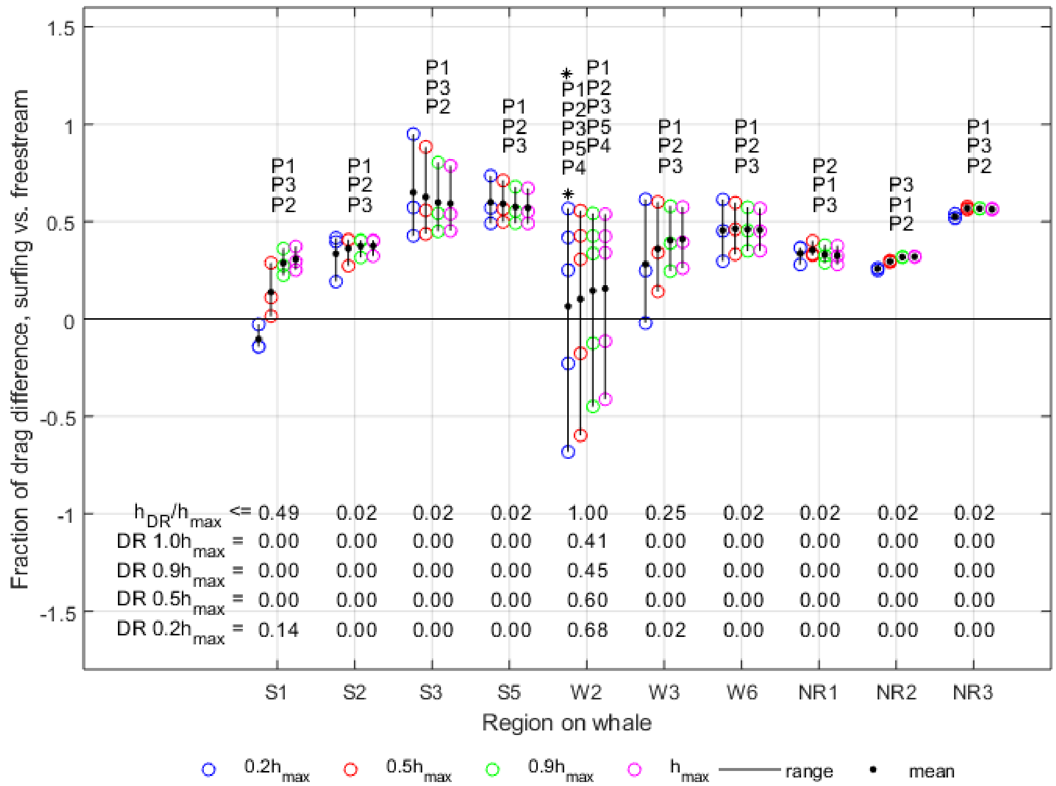


Fig. S7.
Fraction of the difference in drag between skimming at 2 cm off the whale surface and coasting in the freestream (where D_{BL} in Eq. 11 is the drag during skimming) for remora at various regions on a blue whale. Drag reduction of any interest is only available for some remora sizes at S1 and W2. See the legend of Fig. S5 for a detailed explanation of the symbols and table in this figure.

Table S1.

Drag coefficients, C_d, of the whale's body, fins, and of remoras attached to the whale and coasting in the freestream. The values from our LES calculations are reported in the second column. Calculations for the whale were done using both the wetted area for comparison to previous literature and using frontal area for comparison to remora calculations. C_d for the flippers is also shown scaled by planform area as is customary for wing-like objects. The symbols Re_c and Re_{fc} indicate, respectively, the Reynolds numbers calculated based on the whale length *c* and on the flipper chord, *fc*.

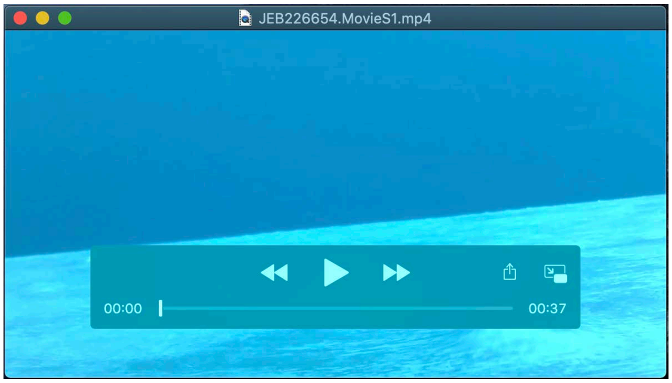
	Current study	(Miller et al., 2004)	(Barrett et al., 1999)	(Cooper et al., 2008)	(Miklosovic et al., 2004)
Wetted Area					
Whale body	C_d = 0.007 $Re_c = 2.27\text{x}10^7$	C_d = 0.00306 Re_c = 1.4-2.8 $\text{x}10^7$	C_d = 0.009 $Re_c = 1\text{x}10^5$		
Wetted Area					
Flippers	C_d = 0.01 (L), 0.02 (R) $Re_{fc} = 2.27\text{x}10^7$			C_d = 0.02-0.06 $Re_{fc} = 1.7\text{x}10^5$	C_d = 0.02-0.04 $Re_{fc} = 5\text{x}10^5$
Frontal Area					
Whale body	C_d = 0.025 $Re_c = 2.27\text{x}10^7$				
Planform Area					
Flippers	C_d = 0.03 (L), 0.06 (R) $Re_{fc} = 2.27\text{x}10^7$				
Frontal Area					
Remora attached to whale	$C_d = 5.05 \text{ x } 10^{-2}$				
Remora in freestream	$C_d = 6.04 \text{ x } 10^{-2}$				

Barrett, D. S., Triantafyllou, M. S., Yue, D. K. P., Grosenbaugh, M. A. and Wolfgang, M. J. (1999). Drag reduction in fish-like locomotion. J. Fluid Mech. 392, 183-212. doi:10.1017/S0022112099005455

Cooper, L. N., Sedano, N., Johansson, S., May, B., Brown, J. D., Holliday, C. M., Kot, B.W. and Fish, F. E. (2008). Hydrodynamic performance of the minke whale (Balaenoptera acutorostrata) flipper. J. Exp. Biol. 211, 1859-1867. doi:10.1242/jeb.014134

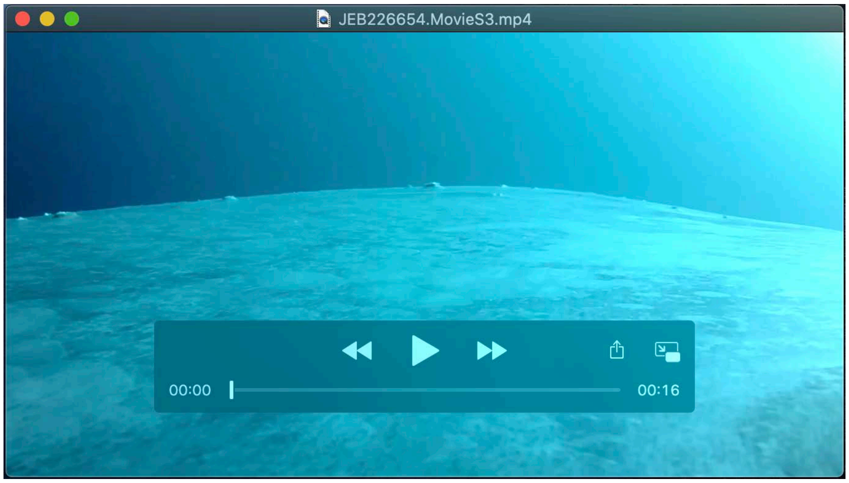
Miklosovic, D. S., Murray, M. M., Howle, L. E. and Fish, F. E. (2004). Leadingedge tubercles delay stall on humpback whale (Megaptera novaeangliae) flippers. Phys. Fluids 16, L39-L42. doi:10.1063/1.1688341

Miller, P. J. O., Johnson, M. P., Tyac, P. L. and Terray, E. A. (2004). Swimming gaits, passive drag and buoyancy of diving sperm whales Physeter macrocephalus. J. Exp. Biol. 207, 1953-1967. doi:10.1242/jeb.00993



Movie 1.
Remora sliding on whale surface while maintaining attachment.

Movie 2.
Remora feeding and skimming along whale body.



Movie 3.
Remora skimming to change positions on whale.

Movie 4.
Remora sliding to change location while maintaining attachment.