SUPPLEMENT: Vertical movements of a pelagic thresher shark (*Alopias pelagicus*): insights into the species' physiological limitations and trophic ecology in the Red Sea

Supplemental Methods

Geolocation methods

The most probable track of the pelagic thresher shark was constructed using the HMMoce package (Braun et al. 2018). This approach combines tag-based measurements of light-levels, sea surface temperature (SST), and depth-temperature profiles, with bathymetry and oceanographic observations and model outputs, to construct likelihoods of the tagged individual's movements. Likelihoods from each of the aforementioned inputs are convolved (i.e., combined via integral transform) in a gridded hidden Markov model that computes an output of posterior probability distributions to estimate the most likely state (position) of the animal at each time point.

Observation-based likelihoods were derived from remotely-sensed SST, light-based longitude, and depth-temperature profile data collected by the tags, using four separate likelihood calculations: *1)* An SST likelihood was generated for tag-based SST values integrated according to an error term (± 1%) and compared to remotely-sensed SST from the Multi-scale Ultra-high Resolution (MUR) sea surface temperature analysis (MUR-SST, 0.01° resolution) (NASA/JPL 2015); *2)* Light-based longitude likelihood was derived using estimates of longitude from GPE2 software (Wildlife Computers, Inc.) that allowed visual checking of light curves; *3)* Depth-temperature profiles recorded by the tag were compared to daily reanalysis model depth-temperature products from the HYbrid Coordinate Ocean Model (HYCOM, 0.08° resolution; Bleck 2002, Chassignet et al. 2007) at standard depth levels available in these products. Individual likelihood surfaces for each depth level were then multiplied together for an overall profile likelihood at that time point. *4)* Ocean Heat Content (OHC) was obtained by integrating the heat content of the water column above the minimum daily temperature to the most shallow depth recorded by the PSAT and included in the HYCOM fields (Luo et al. 2015). The tag detached from the shark prematurely and floated at the surface for 3 days before the "constant depth" trigger initiated Argos transmissions. As such, the deployment end location was estimated by backtracking the consistent trajectory of the drifting tag to its intersection with a calculated bathymetry likelihood where the final maximum recorded depth was assumed to equal bottom depth due to the presumed mortality of the shark (see *Results*). Start location was known, and both start and end locations were fixed in all model runs.

The resulting observation likelihoods, in all reasonable pairwise and triplicate combinations, were convolved with a diffusive movement kernel that allowed swim speeds up to 2 m/s. For full details of the convolution, filtering and smoothing components of the model see Braun et al. (2018). Parameter estimation was performed using an Expectation-Maximization algorithm following Woillez et al. (2016), and model selection used Akaike Information Criterion (AIC). Results from the final smoothing step of the selected model represent the posterior distribution of each state (position) over time. The mean of the daily distributions was used to calculate a most probable track, and confidence intervals represent the 95% contour of the daily distributions.

Autonomous Ocean Glider

The KAUST Seaglider® is equipped with a Sea-Bird Scientific custom CT sensor with an unpumped conductivity cell and dissolved oxygen sensor (Aanderaa Optode 4831). Potential temperature is calculated from the measured pressure and temperature by referencing the temperature to pressure at the ocean surface (Fofonoff and Millard 1983). The Seaglider was programmed to profile from the surface to ~ 610 m at a nominal vertical speed of 0.18±0.02 m/s and moved horizontally at approximately 0.9 km/hr. Two survey transects of the glider line temporally overlapped the pelagic thresher shark's tag deployment from January 20-28, 2020. During this time, the nominal dive cycle of the glider was about 3.3 hours. The glider data was gridded in 2-m depth increments from 0 – 610 m and in 3-km increments over the 80 km of each one-way transect. The pre- and post-calibration activities were carried out at the Coastal and Marine Resources Core Lab (CMOR) glider facility at KAUST and included all ballasting, adjustment operations, and dark counts of the optical sensors necessary before and after the glider deployment.

Time-at-Depth, -Temperature, and -Oxygen

A tag malfunction combined with data transmission issues resulted in some missing depth and/or temperature data in the transmitted time series. In the event depth data was present but missing a concurrent *in situ* temperature measurement, temperature values were interpolated using a 2D-LOESS smoother with 5-d and 150-m spans of the daily depth-temperature profiles. Interpolated values outside the range of variance of the input data were assigned NA values and removed from further analysis. Oxygen measurements from the glider were aligned to the shark's time series data by taking measurements from the concurrent (or temporally most proximate) transect and the closest longitude and depth. Shark time series data occurring at depths > 610 m (< 0.1% of the data) were not assigned dissolved oxygen values because the glider did not survey past 610 m.

Light Comfort Zones of Acoustic Scattering Layers

Downward solar broadband irradiance (W m^{-2}) was measured in 5-min resolution during the daytime at the KAUST meteorological station during the tag deployment (nighttime irradiance data were not reliable and not included). These above-surface measurements were converted into ambient underwater irradiance in the 400 – 700 nm band with a conversion factor of 1.16 μmol quanta s^{-1} W^{-1} (Røstad et al. 2016). Isolume depths were estimated using the equation from Kaartvedt et al. (2017), and informed by the Red Sea light attenuation coefficients and ambient irradiance values corresponding to the light comfort zones of scattering layers 1 – 3 from Røstad et al. (2016).

Supplemental Results

The HMMoce model selection indicated the combination of SST and ocean heat content likelihoods generated the most likely track estimate for the 19-d deployment of the pelagic thresher shark. This suggests that the error in light-based likelihoods was uninformative relative to the scale of the animal's movement. This is not surprising given the typical error in light-based geolocation, particularly in a narrow basin like the Red Sea where longitudinal movements are restricted (Braun et al. 2015). The PSAT successfully reported 67% of the depth and 67% of the *in situ* temperature time series data. Inclusion of interpolated values from the daily depth-temperature profiles increased temperature data coverage to 76%. The inferred mortality of the shark was probably due to the hook placement in the rear of the buccal cavity; our fight time was relatively low based on a previous study of bigeye thresher shark caught using similar methods (Sepulveda et al. 2019), we never removed the shark from the water, and we used a short, one-handed tag applicator on the shark restrained boatside to prevent an overly deep placement of the tag anchor.

References

Bleck R (2002) An oceanic general circulation model framed in hybrid isopycnic-Cartesian coordinates. Ocean Model 4:55–88 https://doi.org/10.1016/S1463-5003(01)00012-9

Braun CD, Skomal GB, Thorrold SR, Berumen ML (2015) Movements of the reef manta ray (*Manta alfredi*) in the Red Sea using satellite and acoustic telemetry. Mar Biol 162:2351–2362 https://doi.org/10.1007/s00227-015-2760-3

Braun CD, Galuardi B, Thorrold SR (2018) HMMoce: an R package for improved geolocation of archival-tagged fishes using a hidden Markov method. Methods Ecol Evol 9:1212–1220 https://doi.org/10.1111/2041-210X.12959

Chassignet E, Hurlburt H, Smedstad O, Halliwell G and others (2007) The HYCOM (HYbrid Coordinate Ocean Model) data assimilative system. J Mar Syst 65:60–83 https://doi.org/10.1016/j.jmarsys.2005.09.016

Fofonoff NP, Millard RC (1983) Algorithms for computations of fundamental properties of seawater. UNESCO Tech Pap Mar Sci 44:53 pp

Kaartvedt S, Røstad A, Aksnes DL (2017) Changing weather causes behavioral responses in the lower mesopelagic. Mar Ecol Prog Ser 574:259–263 https://doi.org/10.3354/meps12185

Luo J, Ault JS, Shay LK, Hoolihan JP, Prince ED, Brown CA, Rooker JR (2015) Ocean heat content reveals secrets of fish migrations. PLoS One 10:e0141101 https://doi.org/10.1371/journal.pone.0141101

NASA/JPL (2015) GHRSST Level 4 MUR Global Foundation Sea Surface Temperature Analysis (v4.1)

Røstad A, Kaartvedt S, Aksnes DL (2016) Light comfort zones of mesopelagic acoustic scattering layers in two contrasting optical environments. Deep Sea Res I 113:1–6 https://doi.org/10.1016/j.dsr.2016.02.020

Sepulveda CA, Wang M, Aalbers SA (2019) Post-release survivorship and movements of bigeye thresher sharks, *Alopias superciliosus*, following capture on deep-set buoy gear. Fish Res 219:105312 https://doi.org/10.1016/j.fishres.2019.105312

Woillez M, Fablet R, Ngo TT, Lalire M, Lazure P, de Pontual H (2016) A HMM-based model to geolocate pelagic fish from high-resolution individual temperature and depth histories: European sea bass as a case study. Ecol Modell 321:10–22 https://doi.org/10.1016/j.ecolmodel.2015.10.024