Toward sustainable and resilient fisheries management for the Humboldt squid deep-water fishery

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Last Updated on September 23, 2024

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Introduction

Background and Motivation

The Humboldt squid (Dosidicus gigas) is one of the most important deep-water fisheries (DWF) globally, playing a crucial role in both the economy and food security. These extraordinarily large squid are particularly sensitive to environmental changes, including fluctuations in sea surface temperature (SST), driven by the El Niño-Southern Oscillation ("ENSO"), that climate change increasingly intensifies. SST plays a pivotal role in determining where squid populations thrive, influencing their migration patterns and spawning grounds (@yu2018ocean). As these temperatures shift, so do the squid, leading to changes in fishing grounds and market demand (Powell, Levine, and Ordonez-Gauger (2022)). Understanding these dynamics is essential for sustainable fisheries management in an era of rapid climate change.

The urgency of this issue is highlighted by recent trends. From 2017 to 2020, the global squid fleet's fishing effort increased by 68%, with most activity concentrated beyond a nation's Exclusive Economic Zone (EEZ) particularly from international vessels (Seto et al. (2023)). This has led to significant geopolitical and environmental concerns, particularly around South America where the Humboldt squid is abundant (Montecalvo et al. (2023)). Although some regional fisheries management organizations, such as the South Pacific Regional Fisheries Management Organization (SPRFMO), have attempted to introduce regulations to moderate squid fishing, most squid stocks on the high seas remain largely unregulated. This lack of regulation, coupled with the sensitivity of squid populations to environmental changes, underscores the need for comprehensive research and effective management strategies.

To address these challenges and seize opportunities for sustainable management, it is crucial to understand how sea surface temperature (SST) changes will affect the Humboldt squid. While some research has begun to explore the impact of sea surface temperature (SST) on the Humboldt squid, few studies have connected these findings to policy implications (Yu and Chen (2018)). We propose to investigate the sensitivity of this fishery to climate change, with a particular focus on the implications for policy interventions. Our goal is to provide policymakers with the necessary data and insights to make informed, sustainable management decisions. Specifically, we will address the following research questions:

- How do fluctuations in sea surface temperature influence the distribution and abundance of Humboldt squid?
- What are the subsequent shifts in fishing demand and potential conflicts among fisheries?

- What specific challenges and opportunities for management enhancement exist n light of changing SST?
- What policy recommendations and fisheries management strategies can be developed to manage Humboldt squid fisheries sustainably in the context of climate change?
- How the relevant RFMO and DWF fleets or adjacent countries can collectively contribute to the sustainable management of jumbo flying squid in the context of climate change?

Approach

The project will be conducted in three phases:

Phase One: Literature review

We will begin with a review of scientific literature and existing studies on biological and ecological characteristics of Humboldt squid, including their life cycles, breeding patterns, and feeding behaviors. We will also compile information on how changes in SST have historically affected squid populations and identify key indicators of climate resilience. In addition, we will review socioeconomic studies that highlight the economic importance of Humboldt squid fisheries, their role in local economies, and the impact of environmental changes on these aspects.

Phase Two: Structural model development

In the second phase, we will develop a data-driven fishery model to simulate future SST scenarios and predict Humboldt squid responses. This model will integrate historical and current data from Global Fishing Watch and SPRFMO, as well as bioeconomic parameters in the existing study of this fishery. We will use this model to analyze the migration patterns of these squid in response to changing SST to predict shifts in fishing demand and the potential for conflict among fisheries.

Phase Three: Policy review and recommendations

Finally, we will assess various fisheries management strategies specific to individual country and regionsY, such as voluntary seasonal closures and enforced fishing moratoriums, to identify their effectiveness in addressing the challenges posed by climate change and overfishing. This will help us develop evidence-based policy recommendations aimed at ensuring the future profitability, resiliency, and sustainability of the Humboldt squid fishery.

Deliverables

- **Kickoff meeting**: Initial meeting with EDF to align on project priorities.
- **Literature review**: In-depth review of existing knowledge on Humboldt squid ecology, distribution, and response to SST fluctuations.
- **Model development**: A model predicting Humboldt squid responses to various climate change scenarios, integrating empirical data on fishing effort and catch.
- **Draft white paper**: A report on the impact of climate change on Humboldt squid fisheries, including policy recommendations supporting the sustainable management of the sector.

1 Methods

1.1 Data sources

1.1.1 Fishing effort

We use satellite-based individual vessel monitoring AIS data processed by Global Fishing Watch (Kroodsma et al. (2018)). We use the V3 pipeline table `pipe_ais_v3_published.messages`. Variables of interest within this table include the following (descriptions are taken directly from the schema for `pipe_ais_v3_published.messages`):

- `ssvid`: source specific vessel id; MMSI for AIS
- `hours`: time since the previous position in the segment
- `timestamp`: timestamp for position
- `lon`: longitude
- `lat`: latitude
- `night_loitering`: 1 if the seg_id of every message of a squid_jigger that is at night and not moving, 0 if not.

In order to minimize noisy data, we only include AIS messages that have a `clean_segs` boolean (i.e., all messages must have `good_seg` boolean and must not have an `overlapping_and_short` boolean). We filter to just those messages where `night_loitering = 1`. For squid jigging vessels, GFW uses the heuristic of night loitering to identify when they are fishing. Therefore, any `hours` where `night_loitering = 1` can be classified as `fishing_hours`

We take the raw high-resolution AIS data and aggregate `fishing_hours` spatially (by 0.5x0.5 degree pixels, which are roughly 55.5km x 55.5km at the equator), temporally by month, and by flag. We currently process data from 2024-06-30 through 2024-06-30.

Here we summarize these data (Table 1.5):

1.1.2 Vessel info

Vessel characteristics data processed are by Global Fishing Watch (Park et al. (2023)). We use the V3 pipeline table `pipe_ais_v3_published.vi_ssvid_v20240601`. Variables of interest within this table include the following (descriptions are taken directly from the schema for `pipe_ais_v3_published.vi_ssvid_v20240301`):

Table 1.1: Summary statistics for the Global Fishing Watch squid jigger effort dataset.

(a) Data summary

Name	gridded_time_effort_by_fl...
Number of rows	57
Number of columns	6
Column type frequency:	
character	1
numeric	4
POSIXct	1
Group variables	None

Variable type: character

skim_variable	n_missing	complete_rate	min	max	empty	n_unique	whitespace
flag	10	0.82	3	3	0	9	0

Variable type: numeric

skim_variable	n_missing	complete_rate	mean	sd	p0	p25	p50	p75	p100	hist
lon_bin	0	1	40.88	126.15	-172.00	-85.50	110.50	133.50	166.50	
lat_bin	0	1	16.93	23.78	-19.50	-5.50	15.00	42.50	47.50	
fishing_hours	0	1	35.78	74.90	0.08	5.06	11.64	24.68	366.01	
fishing_kw_hours	0	1	43824.26	87225.35	157.74	4662.58	9789.62	37702.92	412724.69	

Variable type: POSIXct

skim_variable	n_missing	complete_rate	min	max	median	n_unique
month	0	1	2024-06-01	2024-06-01	2024-06-01	1

- `ssvid`: source specific vessel id; MMSI for AIS
- `best.flag`: best flag state (ISO3) for the vessel

- `best.best_vessel_class`: best vessel class for the vessel (using official registry information where available, or the GFW vessel characteristics algorithm where not available)
- `best.best_engine_power_kw`: best engine power (kilowatts) for the vessel (using official registry information where available, or the GFW characteristics algorithm where not available)
- `activity.active_hours`: hours the vessel was broadcasting AIS and moving more than 0.1 knots
- `activity.offsetting`: true if this vessel has been seen with an offset postition at some point between 2012 and 2019
- `activity.overlap_hours_multinames`: the total numbers of hours of overlap between two segments where, over the time period of the two segments that overlap (including the non-overlapping time of the segments), the vessel broadcast two or more normalized name, where each normalized name was bradcast at least 10 or more times. That is a bit complicated, but the goal is to identify overlapping segments where there were likely more than one identity. (this should be 0; if it is > 0, it can be used as a filter to remove potentially erroneous/noisy vessels)

We filter to just those vessels where `best.best_vessel_class = squid_jigger`. Additionally, to reduce noise, we filter out vessels that broadcast exceedingly infrequently (i.e., `activitiy.active_hours < 24`) or are noisy/spoofing/offsetting vessels (i.e., `NOT activity.offsetting OR activity.overlap_hours_multinames > 0.`) They are simply not reliable and will not provide good effort estimates. This leaves us with 1,561 squid vessels for our analysis.

1.1.3 Sea surface temperature (SST)

Sea surface temperature (SST) data come from NOAA's Optimum Interpolation Sea Surface Temperature (OISST) version 2.1 (Huang et al. (2021)), which were downloaded from their Coast Watch ERDDAP server. The raw data are provided globally at 0.25x0.25 degree daily resolution. We aggregate the data to 0.5x0.5 degree monthly resolution by calculating the mean, standard deviation, minimum, and maximum SST for each 0.5x0.5 degree pixel and month.

Here we summarize these data (Table 1.5):

We can also look at a map of SST, using August 2024 as an example (Figure 1.1).

Table 1.5: Summary statistics for the sea surface temperature dataset.

(a) Data summary

Name	sst_data_aggregated
Number of rows	556490986
Number of columns	7
Column type frequency:	
numeric	6
POSIXct	1
Group variables	None

Variable type: numeric

skim_variable	n_missing	complete_rate	mean	sd	p0	p25	p50	p75	p100	hist
mean_sst	0	1.00	13.90	11.75	-1.8	1.13	14.86	25.76	38.16	
sd_sst	4875640	0.99	0.10	0.13	0.0	0.03	0.07	0.13	5.27	
min_sst	0	1.00	13.80	11.75	-1.8	0.99	14.66	25.66	37.76	
max_sst	0	1.00	14.01	11.76	-1.8	1.27	15.05	25.86	38.58	
lon_bin	0	1.00	-8.71	109.24	-180.0	-107.00	-18.50	87.00	179.50	
lat_bin	0	1.00	0.50	48.49	-78.5	-42.00	-4.50	38.50	89.50	

Variable type: POSIXct

skim_variable	n_missing	complete_rate	min	max	median	n_unique
time	0	1	2016-01-01	2024-08-01	2020-05-01	104

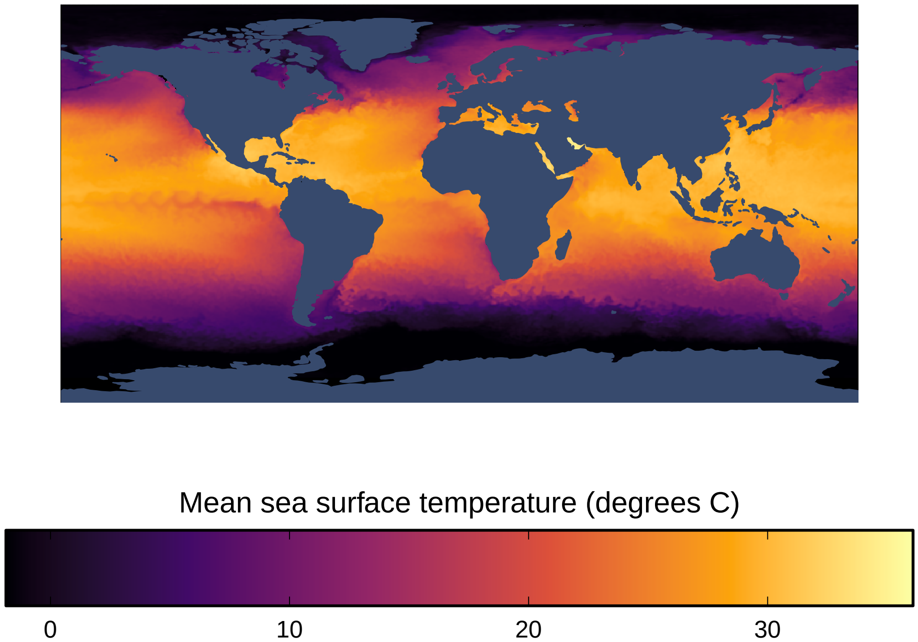

Figure 1.1: Map of mean sea surface temperature in August 2024, using 0.5x0.5 degree pixels.

Aggregating across the mean sea surface temperatures of each pixel, we can calculate the mean global sea surface temperature over time (fig-sst-time-series). This allows us to see both seasonal trends, and what appears to be a generally increasing trend over time.

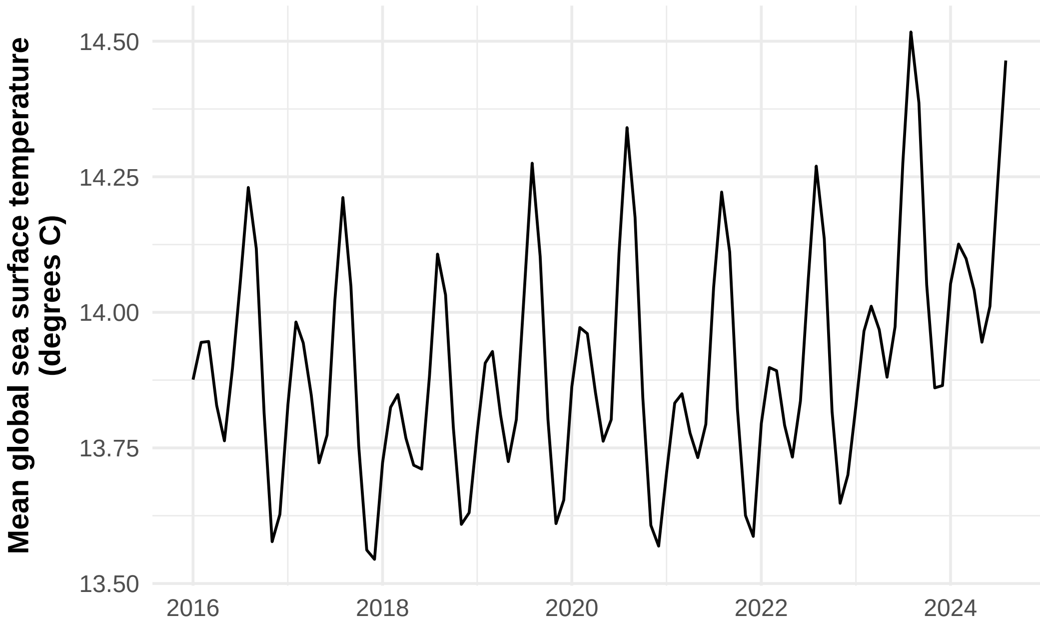

Figure 1.2: Time series of global mean sea surface temperature.

2 Results

2.1 Fishery summary

Our analysis includes 1,561 squid vessels spread across 52 flags. For each flag, we can look at the total number of unique vessels and total engine power (kW) (Figure 2.1). China dominates the fleet.

Figure 2.1: Squid jigger vessel summary by flag, showing the total number of unique vessels and total engine power (kW)

Next we can look at at a map of squid fishing effort (Figure 2.2), aggregating effort across effort and time for each pixel across the entire processed time series (2024-06-30 through 2024-06-30). EEZ boundaries from Marine Regions v12 are shown in orange (Institute (2023)).

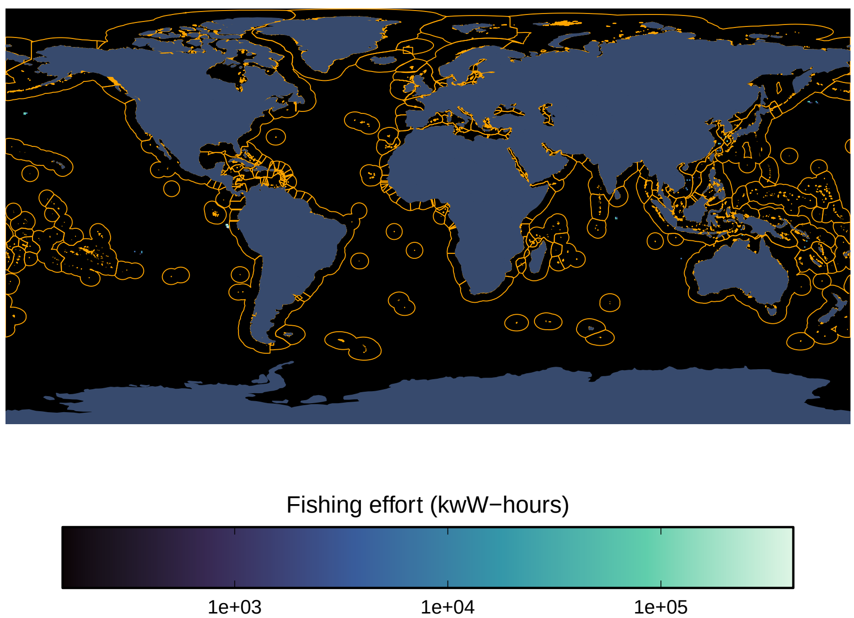

Figure 2.2: Map of squid fishing effort, aggregating effort across effort and time for each pixel. EEZ boundaries from Marine Regions v12 are shown in orange.

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