# Movement of the starry smooth-hound shark *Mustelus asterias* in the North Sea

# Introduction

*Problem Statement*

* Knowledge on migratory fish species with complex life cycles hard to gather but necessary to increase in order to manage species better in the future
  + One such species is the starry smooth-hound *Mustelus asterias* (+ 1-2 sentences about the species)
    - Demersal triakid shark (IUCN: near threatened, decreasing population trend) with broad distribution in the NE atlantic and a complex life cycle involving biannual reproduction and a sex-specific annual migration
    - *Refer to subchapter about M. asterias (with more in-depth info)*
  + Until recently, close to nothing about the seasonal presence of M. asterias in the Belgian Part of the North Sea and especially the Scheldt Estuary was known
  + But catches are increasing, alongside the species’ commervial value (Griffiths et al., 2002 and ICES, 2017)
  + Advanced technology is required to follow the movements of demersal, migratory species (transition to telemetry and ADST)

## Aquatic Telemetry

*See chapter 2.1 of LP\_thesis\_manuscript\_20230504.pdf* 🡪 overview over acoustic & archival telemetry

* State advantage of ADST: gathering knowledge on horizontal movement within areas of acoustic receiver array, and additionally gaining fine-scale data beyond those receiver areas to investigate movement and migrations outside the receiver areas

### Geolocation Modelling

*See chapter 2.2 and 2.3 (first 2 paragraphs) of LP\_thesis\_manuscript\_20230504.pdf* 🡪 brief overview of geolocation models and behavioural states

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Figure : Example of a trajectory that was geolocation modelled. From Goossens et al., 2023.

## The starry smooth-hound shark *Mustelus asterias*

*See chapter 2.4 of LP\_thesis\_manuscript\_20230504.pdf*

Information about:

* General characteristics *(see chapter 2.4)*
* Reproduction *(see chapter 2.4.1)*
* Feeding (prey and potential predators, *see chapter 2.4.2)*
* Migration (*see chapter 2.4.4)*

*Transition to knowledge gaps about the species and aims of the work*

Knowledge gaps

* Migration: Exact timing unknown, and vertical behaviour during migration unstudied, but relevant to assess to enable incorporation of different behavioural states into geolocation modelling
* Role of the Western Scheldt in the reproductive cycle hypothesized to be relevant (e.g. since Eastern Scheldt is a confirmed pupping ground) but not studied yet

The sex bias in \*M. asterias\* migration behaviour and seasonal presence in the North Sea has been addressed by @breve\_2016 and @griffiths\_2020, however, the vertical behaviour during the seasons has not been assessed in detail yet. Investigating the raw depth data from DST bears potential in revealing behavioural patterns (that potentially differ per season and sex) that are relevant to inform species management, regarding fishing restrictions to avoid bycatch, or protecting the species in vulnerable life stages like parturition.

Moreover, the role of the Western Scheldt in the species’ reproductive life cycle is hypothesized to be relevant. The adjacent estuary of the Eastern Scheldt is a confirmed pupping ground, and both adult females and neonates have been reported in summer just outside of the Western Scheldt[^1].

[^1]: Verhelst, Pieterjan (\*personal communication\*), April 25, 2023.

Until now, however, the seasonal presence of \*M. asterias\* in the Western Scheldt has not been studied.

Therefore, this work aims to assess seasonal and sex-related differences in movement patterns of \*M. asterias\* on two different scales/domains:

## Aims of this work

1. Describe and characterise presence of M. asterias in the Western Scheldt
   1. Identify patterns of presence linked to season and sex
   2. identify potential hotspots that could become a focal point of species management measures in the area
2. Describe and characterize the vertical patterns of different phases in their annual movement pattern, more specifically focusing on the questions:
   1. Are there seasonal differences in vertical behaviour?
   2. Are there differences between sexes?

# Materials and Methods

*See chapter 3 of LP\_thesis\_manuscript\_20230504.pdf*

## Tagging Procedure

*See chapter 3.1 of LP\_thesis\_manuscript\_20230504.pdf*

## The Study Area

### Belgian Part of the North Sea and Scheldt Estuary

*See chapter 3.2.1 of LP\_thesis\_manuscript\_20230504.pdf*

#### English Channel

*See chapter 3.2.2 of LP\_thesis\_manuscript\_20230504.pdf*

### Greater North Sea Area

## The Permanent Belgian Acoustic Receiver Network

*See chapter 3.3 of LP\_thesis\_manuscript\_20230504.pdf*

## Data Management

*See chapter 3.3.1 of LP\_thesis\_manuscript\_20230504.pdf*

## Ethics Statement

*See chapter 3.4 of LP\_thesis\_manuscript\_20230504.pdf*

Data Analysis and visualization

*See chapter 3.5 of LP\_thesis\_manuscript\_20230504.pdf*

Acoustic Detections

* Summary of each receiver station per sex and month
  + *Mention more? The only thing I really did was doing heatmaps…*
* Include Residency Indices yes/no?

Data Storage Tags

*See chapter 3.5.2 and 3.5.2.1 of LP\_thesis\_manuscript\_20230504.pdf*

# Results

## Tagged Animals

*See chapter 4.1 of LP\_thesis\_manuscript\_20230504.pdf* 🡪 table with info about animals

## Acoustic Detections

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Figure : All acoustic detections of M. asterias. The female/male symbol shows the data of tagging.

* Most detections inside the WS1 array (96 %)
* Mostly females detected (97 %)

### Detections of females in the Western Scheldt

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Figure : Number of detections of females per receiver station. The number inside the rectangles refers to the amount of individuals detected.

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Figure : Map for reference about station locations.

#### Detections of females at station OG10 in summer 2019

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Daily number of detections at station OG10 in 2019. All tags are inside female sharks. 3 tags, namely 308, 299 and 297 have more detections at station OG10 than the remaining tags. This is further shown in the boxplots with the residency indices below.

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The pattern visible from the heatmap above can further be seen here, where females with higher residency indices (RI = number of days detected in 2019 / number of days between the first and last detection of a shark at station OG10 in 2019) have higher numbers of detections per day.

## Data Storage Tags

*For table with info on retrieved tags, see table 3 in chapter 4.3 of LP\_thesis\_manuscript\_20230504.pdf*

### Raw depth and temperature logs

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Figure : Raw depth and temperature logs of the female (left, tag 308) and the male (right, tag 321) M. asterias.

Between Oct and Dec 2018, the female went deeper than the tag’s depth limit of 68m.

### Autocorrelation

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Figure : Autocorrelation plots of female (tag 308, left) and male (tag 321, right). Lag of characteristic points (autocorrelation = max, min and 0) noted in blue.

### Daily summary statistics

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Figure : Daily median and depth range of female (tag 308, left) and male (tag 321, right) shark.

### Seasonal periodicities

*I will (try to) do a wavelet scalogram for periods of 2 – 72 hours, right now I only did the wavelet analysis for the daily summaries (since that did not take as long to run). So hopefully there will be one wavelet scalogram instead of five fft periodograms*

#### Female (tag 308)

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Figure : FFT periodograms of the female shark (tag 308)

* Both summer periods: only 12h periodicity
* Slight 24h periodicity in winter
* Winter migration peak periodicity of 24h, but for summer migration no periodic pattern standing out

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Description automatically generated with low confidence

* Simple linear regression shows that minimum depth is correlated with the fraction illuminated by the moon. That could mean the the shark goes to shallower depths during full moon to visually prey there, as suggested by Griffiths et al., 2020. The residuals seem to follow a normal distribution (as can be seen in the qq-plot and the density plot), but the R^2 is very low. An effect that potentially is related to the depth use of M. asterias, especially in the English Channel region is the intensity of tidal currents. While this variable is difficult to test for, since the exact location of the individual is not known, it is hypothesized that tidal currents also have an influence on the vertical behaviour, in addition to the light provided by the moon. This could already be shown in visually hunting sharks like the great white shark *Carcharodon carcharias* (?) (ref)

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Description automatically generated

* Final interpretation: the depth use of the shark is correlated with the moon phase (which is illustrated in the plots as the fraction of the moon illuminated).
* Since both the depth per day and the depth per night are correlated with the fraction of the moon illuminated, it is inferred that the preying behaviour is not influenced by the intensity of moonlight, i.e. a sole influence of moonlight intensity on preying and foraging behaviour (that is thought to be swimming to shallower depths)
* Instead, it is hypothesized that vertical activity, especially by the female in winter, might be related to the intensity of tidal currents. This relationship is more complex to address and therefore beyond the scope of this work, since tidal currents differ strongly with location.

#### Male (tag 321)

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Figure : FFT periodograms of the male shark (tag 321)

* Two summer periods differ: summer 2018 mostly 24h periodicity and in summer 2019 12h and 24h periodicities almost equally present.
* All three migration periods: 12 h periodicities, and in summer migration also 24h periodicity (and less so in winter migration of 2018).

### Wavelet

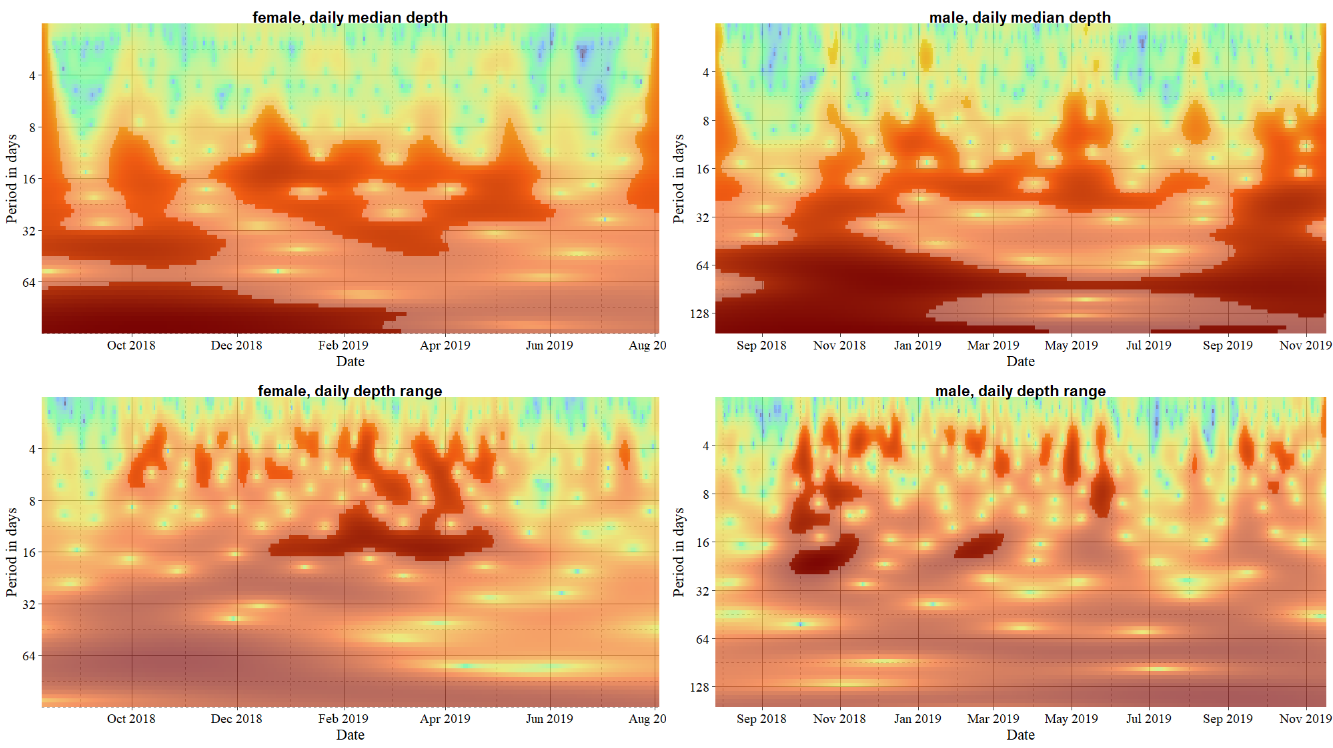


Figure : Wavelet scalograms from daily summary statistics. Left: female (tag 308), right: male (tag 321), top: daily median depth, bottom: daily depth range

Horizontal Distance (from the geolocation model output)

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Figure : green: female (tag 308), purple: male (tag 321)

Female: higher horizontal distance than male, peaking at 30km in one day in mid-May, 2019. Male: highest distance at ~15km at the end of October, 2019.

### Combination of Acoustic and Data Storage Information

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Figure : Raw depthlog of tag 308 from may 2019 to end of logging in Aug 2019 overlayed with acoustic detections, coloured by receiver station.

Although the female’s DST stopped logging in Aug 2019, the acoustic sensor still worked and the female was detected at the Birkenfels station in October 2019, suggesting that it left the area around that time.

Also, high overlap between acoustic detections and DST log between second half of may and first half of June, and second half of July and first half of August.

# Discussion

## Acoustic Detections

#### Seasonal Presence of females in the Western Scheldt

There are no acoustic detections at all [cf. @fig-abacus] between November and April in all years with acoustic detections (2018-2020). This indicates a seasonal presence of \*M. asterias\* in the Western Scheldt between April and November. The months of May and October had the most acoustic detections while most individuals were detected in August. Therefore, it is difficult at this point to narrow down the time window of April until November and it is recommended to study the seasonal presence of \*M. asterias\* in the Western Scheldt with greater detail in the future.

A hotspot of seasonal presence of mature \*M. asterias\* females seems to be the receiver OG10. According to fishermen, the area offshore from Zoetelande (north of Dishoek) is a \*M. asterias\* fishing hotspot, so the coastal waters between Diskoek and Zoetelande are suggested to be important for the species. Whether or not the potential aggregations of mature females is related to parturition cannot be said at this point.

Another important fact to consider is the biannual reproductive cycle of \*M. asterias\* and whether that implies differing habitat use between years of pregnancy and years without a pregnancy.

In the future, it could be helpful to assess if adult females are pregnant at the time of release, through ultrasonography or the use of sex steroid hormones, both of which have already been employed to determine pregnancy in sharks [@awruch\_2014; @anderson\_2018; @fujinami\_2020; @fujinami\_2021]. This would allow for further clarification if the Western Scheldt is used as a pupping ground, and if it might be a relevant area for non-pregnant females, too.

An area with little presence of the tagged \*M. asterias\* individuals is the Western Scheldt upstream past Vlissingen. Shallow and sheltered coastal habitats are thought to be suitable pupping grounds for sharks in general [@speed\_2010] and for \*M. asterias\* in particular [@ellis\_2004; @ ellis\_2005]. The low number of acoustically detected sharks (38 detections across the whole study period) indicates that the waters past Vlissingen are not as frequently used as the waters around Dishoek.   
The Scheldt Estuary is influenced by two water bodies from the North Sea, the Channel water and the Continental coastal water [@wolff\_1973, see @ sec-mmscheldtBPNS]. The boundary between those bodies is approximately 30 km offshore from the Estuary, and in the Continental coastal waters nutrients are abundant (unlike in the Channel water). This, together with monthly water temperatures above 15 °C between June and September make the (Western) Scheldt Estuary a potentially suitable pupping habitat. The fact that few sharks were detected upstream past Vlissingen could be due to low salinities, or to anthropogenic influences like dredging. This, however, should be further investigated in follow-up studies.

\*M. asterias\* might leave the area of the Western Scheldt during winter because of decreasing water temperature. Since water temperatures are a main predictor of elasmobranch occurrence [@martin\_2010]. The warmer waters in the Channel area might be favourable especially for gestating females since higher water temperatures increase metabolic rate and thereby improve embryo development [@hurst\_1999].

<!-- It was therefore unexpected to have only 38 acoustic detections in the WS2 array which can be considered more sheltered than the WS1 array, and no detection in the WS3 array. This, together with the high numbers of detections in the WS1 array indicates that the waters around the WS1 array are more utilized and thus more relevant for the species as compared to the Western Scheldt estuary upstream past Vlissingen. Possible reasons for the low presence of \*M. asterias\* can be salinity (the salinity tolerance of the species), limited availability of prey, or water quality. -->

* Season of peak presence of adult females: April – September
* Area around dishoek and zoetelande = hotspot, estuary upstream past Vlissingen: not so important
  + Only some tagged females are very present in the area, indicating that there could be differences in habitat use between pregnant and non-pregnant females.
    - Whether that implies that non-pregnant females use other parts of the estuary (e.g. receiver WN2 that also saw many detections in 2018) or that they use completely different areas cannot be said at this moment
  + No direct evidence of pupping, (more investigation needed), but presence of females in summer (somewhat sheltered area, warm temperatures, i.e. good conditions for pupping) suggest it
* The absence of M. asterias in the Western Scheldt in winter might be related to temperature, since
  + Waters in the Western Scheldt drop to ~5 degrees in winter
  + temperature often controls seasonal species occurrence
  + waters in e.g. the English channel are warmer in winter, so especially for gestating females it might be faviourable to move into warmer waters in winter to have good conditions for developing pups

## Data Storage Tags

### Seasonal differences in vertical behaviour patterns

*From Figure 7 (daily depth summary)*

Briefly state that due to the demersal lifestyle of the species, shallower depths means a shorewards, horizontal movement of the individual and no vertical movement into the water column

Generally: 12h periodicity refers to resting on the seafloor (pure tidal signal), 24h periods refer to diel vertical migration potentially related to feeding

#### Summer

Due to the demersal lifestyle of \*M. asterias\*, shallower depths in the depthlog indicate a shoreward movement along the seafloor, as opposed to a vertical movement into the water column. If, for example, the depthlog shows shallower depths during the night (\*\*reference to the depthlog detail figure\*\*) that suggests a movement into shallower, coastal waters to feed.

From both recovered DSTs that logged data for over a year, the daily vertical range and median depth are shallower in summer (around 17 m median depth for the female and around 10 m median depth for the male, both with ranges between 0 and 20 m) than in winter.

<!-- This implies that the sharks move into shallow waters at least for a short time per day (the female shark’s daily minimum depth averages 3.7 m between its release on August 2, 2018 and September 25, 2018). -->

The wavelet scalograms of the raw depthlogs [@fig-waveletresults308-1 and @fig-waveletresults321-1] show a difference in periodicity on the hourly scale between males and females. In summer, the female shows mainly a periodicity of 12 h (indicated by band of high power in red colour), which is a pure tidal signal (since from one high tide to the next one it takes approximately 12 h, the same holds true for low tide). This 12 h periodicity and the fact that no other prevalent periodicities show in the wavelet scalogram in the period between August and the end of September 2018, therefore implies that the female itself expresses no to little vertical activity and is only resting on the seafloor.  
The male, on the other hand, shows a periodicity of 24 h. This can be seen as a high-power band in red colours at the 24 h period in the wavelet scalogram on the hourly scale [see @fig-waveletresults321-1].  
This is thought to show diel vertical migration, which has been observed in several shark species, for example the spiny dogfish \*Squalus acanthias\* [@carlson\_2014]. Diel vertical migration is believed to be related to foraging and feeding, following the nightly vertical migration of zooplankton to feed [@griffiths\_2020].

#### Migration into winter habitat

From September 25 for the female and October 21 for the male, the daily depth gets progressively deeper over a period of around 15 to 20 days, which potentially is the migration period of these individuals.

Interestingly, both individuals go to the maximum depth logged by the tag within the logging period directly the potential migration into the winter habitat. During this time, the female shark goes to depths below the tag’s measuring limit of 68 m, as indicated by a straight line in the raw depthlog [see @ fig-dst308-1]. This provides further evidence of the species utilizing deeper waters than previously thought, as argued by @griffiths\_2020 that found a maximum recorded depth of 118 m in a female shark in December [@griffiths\_2020, S4].  
The male shark goes to depth between 40 and 45 m. Both individuals stay at their respective maximum depths for approximately one month (the female between the end of October until the end of November, 2018 and the male between the start of November until the start of December, 2018). This behaviour could be related to resting after the migration or escaping potential predators. This was not further assessed at this point and could be subject of future studies.

#### Winter

During the winter months between December and March, both individuals show roughly biweekly periods of increased vertical activity, which can be seen in both the daily summary statistics and the wavelet scalogram of the daily depth range [see @fig-dstsum, @fig-waveletresults308-2 and @fig-waveletresults321-2]. This could be linked to moon phases, which was further assessed in (\*\*ref to moon phase section\*\*) and will be discussed in (\*\*ref to moon phase discussion section\*\*).

#### Migration into summer habitat

In spring, roughly between April and May, the daily median depth gets shallower in a stepwise manner for both individuals which might be the migration into the summer habitat. The female (tag 308) was detected in the receiver areas of the BPNS and WS1 in the year following its release, proving the individual’s return and providing further evidence of philopatric behaviour for the species [@breve\_2016; @griffiths\_2020].

The start and duration of the summer migration cannot be identified as clearly from the daily median depth as the winter migration since the depth does not decrease drastically over a period of less than three weeks. From the wavelet scalograms of the raw depthlog (\*\*ref to figures\*\*) the time of potential migration into the winter habitat shows a band of high power throughout periods from 4 to 64 hours (i.e., high prevalence of these periods), albeit this is does not significantly differ from white noise (and is thus slightly transparent). But since the winter period also involves vertical activity, it is not clearly visible in the scalograms either when the migration into the summer habitat starts. Therefore, a more detailed investigation of the difference in vertical movement between the migration into the winter and the summer habitat could be an interesting focus for future studies.

* Vertical range and median depth in summer much shallower than in winter
* Depth increases fast (over 7-10 days) between summer and winter 🡪 potential migration to winter habitat
* In spring, roughly between April and may, the depth gradually decreases 🡪 potential migration to summer habitat
* In winter, the female displays shallower daily depths in a roughly biweekly pattern. The same is visible for the male, but less clearly

*From Figure 8 and 9 (periodograms of depthlog subsets)*

* Migrations to winter and summer show different characteristics and thus suggest different behavioural patterns and routes
  + The female seems to feed during the winter migration but not during the summer migration (sign of pregnancy?)

### Sex-specific vertical behavioural patterns

*From Figure 7 (daily depth summary)*

* Looking at the daily summaries: the overall patterns visible are the same for female and male (shallow depth in summer, then stark depth increase, then winter depth with periodically shallower and deeper depths (although the male does not go as deep in winter as the female), then gradual depth decrease between April and may, and then shallow depths in summer again
  + Autocorrelation plots: same scale of seasonality between male and female
  + Depth use: female goes deeper than male, and also depth > 68m (tag’s limit) go in line with results from Griffiths et al., 2020 that document 118m which is thought to be unusually deep for this species 🡪 so generally M. asterias might go deeper than previously thought

*From Figure 8 and 9 (periodograms of depthlog subsets) and 10 (wavelet scalograms)*

Spectral analyses show different periodicities in the vertical movement between the male and the female

* The male shark feeds and sometimes rests during summer while the female shark mostly rests
  + A picture containing text, diagram, line, plot

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* During winter, the male shark does not rest but only feed and the female shark rests and periodically feeds 🡪 potential connection to lunar cycles
  + The wavelet scalogram of daily depth range has roughly biweekly periodicities of 3-7 days. This shows the duration of patterns with reduced vertical activity (i.e. from the depth range wavelet scalogram of tag 308 it can be inferred that there are periods of reduced vertical activity that occur biweekly between January and may, 2019, and last for 3-8 days. These patterns partially can be seen for tag 321 as well, albeit not as clear.
  + The female potentially is in the English Channel during winter, an area with tidal currents amongst the strongest in the world, thus it might be possible that the shark exhibits less vertical activity during periods of strong tidal currents and more vertical activity during weaker tidal currents. Furthermore, the male sharks potentially is around the east coast of England off Norwhich, and area with weaker tidal currents and might have less of an incentive to have a bimodal vertical activity pattern.
* During periods of high changes of daily median depth (i.e., potential migration):
  + the female seems to not rest during the winter migration (and the male rests and feeds), and the male seems to rest more
  + the female does not show a clear activity pattern during the summer migration, indicating that she might not have a 24h diel feeding pattern and thus does not feed, suggesting pregnancy
  + tidal signals during potential migration periods: selective tidal stream transport?

### Influence of moon phases on vertical activity of \*M. asterias\*

* Simple linear regression shows that minimum depth is correlated with the fraction illuminated by the moon. That could mean the the shark goes to shallower depths during full moon to visually prey there, as suggested by Griffiths et al., 2020. The residuals seem to follow a normal distribution (as can be seen in the qq-plot and the density plot), but the R^2 is very low. An effect that potentially is related to the depth use of M. asterias, especially in the English Channel region is the intensity of tidal currents. While this variable is difficult to test for, since the exact location of the individual is not known, it is hypothesized that tidal currents also have an influence on the vertical behaviour, in addition to the light provided by the moon. This could already be shown in visually hunting sharks like the great white shark *Carcharodon carcharias* (?) (ref)
* Final interpretation: the depth use of the shark is correlated with the moon phase (which is illustrated in the plots as the fraction of the moon illuminated).
* Since both the depth per day and the depth per night are correlated with the fraction of the moon illuminated, it is inferred that the preying behaviour is not influenced by the intensity of moonlight, i.e. a sole influence of moonlight intensity on preying and foraging behaviour (that is thought to be swimming to shallower depths)
* Instead, it is hypothesized that vertical activity, especially by the female in winter, might be related to the intensity of tidal currents. This relationship is more complex to address and therefore beyond the scope of this work, since tidal currents differ strongly with location.

## The potential of ADST for *M. asterias*

* In this study: small sample size plus low retrieval rate of DST 🡪 only limited overlap between information gathered from acoustic and dst data
* General: high potential to gain in-depth insights about horizontal and vertical behaviour on different temporal scales 🡪 well-suited tracking method for *M. asterias*
* Acoustic detections improve geolocation modelling which is especially helpful in highly mixed areas with homogeneous bathymetry like the Schelde estuary, since these are areas that where geolocation models are less reliable since they cannot make out a definite position by depth and temperature if these variables are more or less constant throughout the area.

### Tag recoveries and possible tagging effects

% - 5% tag to body weight ratio. study by brown and japsen (or sth), eels and cyprinid are more robust --> pieterjan, here ratio max 1.4% so from the study's point of view, the sharks should it have taken alright

\*\*effect: as soon as you do any observation on animals, you interfere with the system

that means: all tagging has an effect\*\* discuss

### Possible death reasons of short term dst’s

- Tagging consequences

- High sensitivity (verhelst, pers. Comm.)

- Not likely: death bc of seals (no temp increase)

- Laying dead on seafloor (tidal signal)

Limits of the datasets

• There are ~10 000 detections within ~2 yrs but compared to other studies (ref to other studies!) this is not that much.

• the horiz resolution of receivers, esp in/around the WS is not good bc rather receiver gate than array to monitor species swimming into/out of the Scheldt river (= different use case scenario: receiver array needed to resolve locations of sharks better, and to e.g. enable triangulation) 5.8. Limits of the data storage tag dataset

• Female shark: deeper than tag depth limit (68m): geolocation model inaccurate, shark putatively went into the Hurd deep (MRGID: 3321) in English channel

• Only one individual per sex: not reliable, no statistics possible

## Reflection of the chosen analyses

Since this work did not involve fieldwork but instead was purely focused on the analysis of the acoustic detection and data storage tag dataset, the chosen analyses will be reflected upon in the following.

### Acoustic detections

For this work, the acoustic detection data were analysed in an exploratory way. Heatmaps with the number of detections per receiver station and month proved to be a suitable method of investigation. In the future, the detections of single females during summer could be look at in detail to assess if there are differences in presence around certain receivers that could indicate pupping. A useful piece of information for such investigations would be to assess the reproductive status of tagged females (i.e., if the individual is pregnant or not) upon release, as already argued in @sec-disc-acousticdetections.

### Autocorrelation

*See chapter 5.4.1 of LP\_thesis\_manuscript\_20230504.pdf* (without the plots)

### Wavelet

Conducting a continuous wavelet transform (CWT) and thereby resolve prevalent periodicities in the time domain proved to be a main analysis tool in this study. Furthermore, performing CWT on the raw depthlog and the daily summary statistics allowed for different scales of periodicities and was able to provide further proof of patterns that could already been seen in the daily summary statistics in @fig-dstsum.   
CWT was preferred over Fourier Transformation (FT) due to its ability to resolve periodicities in the time domain. While FT can also be performed on subsets of the depthlog, this manual separation introduces a bias and within that subset, the periodicities are not resolved in the time domain.  
The resolution in the time domain of CWT comes at the cost of a lower resolution both in the time and frequency domain. Thus, FT provides a first step of spectral analysis and can give insights into generally existing patterns of periodicity (as shown in -@sec-annexfft), but CWT allows for unbiased assessment of change of prevalent periodicities in time of time series data.  
In the wavelet scalograms on the hourly scale, only periods in winter were significantly present and are shown as fully opaque in the plots [@fig-waveletresults308-1 and @fig-waveletresults321-1]. In summer, periodicities of 12 h for the female shark and 24 h of the male shark have a high prevalence (indicated by a high power value and a orange/red colour in the scalogram), albeit these are not significant. This is thought to be due to the difference in magnitude of the periodicity during summer compared to the winter period, for example, where overall vertical activity is much higher.

<!-- So, although not unmistakeably discriminable from white noise, -->

Compared to Fourier Transformation, Wavelet transform

* Very useful method to resolve periodicities in the time domain, can give many insights and confirm patterns visible in the daily summaries but more accurately

# Conclusion

The data gathered for this study support previous hypothesis about M. asterias seasonal distribution and migration behaviour, and can add more detailed knowledge in some aspects

* Previous Knowledge: Females tend to be in the Schelde estuary in summer, potentially related to parturition
  + Knowledge gathered from this study: Females are particularly present around the receiver OG10, and their aggregation might extend to Zoetelande (according to fishermen)
* Previous knowledge: Migration behaviour is sex specific, with females primarily going southwards during winter and males primarily going northwards
  + Knowledge gathered from this study: the 2 geolocation model outputs show this trend as well
  + Knowledge gathered from this study: New insights on sex- and season-specific vertical behaviour could be gained: females rest during summer, while males also feed, females show a strong biweekly vertical activity periodicity during winter (males less so), the female potentially does not feed during the summer migration

# Outlook

* Assess if a female is present upon tagging 🡪 hormone sample?
  + Birth Alert Tags: new development
* If possible, install receiver at buoy in zoetelande
* Assess the impact of tagging on pregnant sharks: *can sharks abort pups/release them earlier than originally intended due to stress caused by tagging?*
* Use tags for M. asterias that can log deeper than 68m, since the female went past this depth limit
* First step to improve geolocation model: introduce boundary condition whereby maximum depth of the shark per day == bathymetry depth of that day
  + Then: implement tidal behavioural segmentation by Pedersen 2008