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

# Executive Summary

\*executive summary (400 words): contains a summary of all relevant information documented in the thesis (Introduction, M&M, Results, Conclusion), discuss/mention hypotheses\*

\*\*currently: 378 words\*\*

The starry smooth-hound \*Mustelus asterias\* is a widely distributed demersal shark in the Northeast Atlantic, yet under increasing fishing pressure. To lay the grounds for future species management plans, information on its complex annual migration and residency behaviour is needed.

The movement of fish is commonly studied with electronic tags. A novel technology is the Acoustic Data Storage Tag (ADST), which can be detected by acoustic receivers and additionally logs temperature and water depth in predefined intervals. To access the data logs the tag needs to be recovered.

This study employs ADST to characterise the migration and residency of \*M. asterias\* in the North Sea regarding seasonality and sex.

160 acoustic receivers that can detect ADST are currently installed in the Scheldt Estuary and the Belgian Part of the North Sea (BPNS) as part of the European Tracking Network.

In 2018 and 2019, 30 adult \*M. asterias\* (19 females, 11 males) were equipped with ADST-V13TP (Innovasea, 518 days estimated battery life) in the Scheldt Estuary. 18 individuals (14 females and 4 males) were detected 10940 times by the acoustic receivers between July 2018 and July 2020.

All detections were between April and November, suggesting seasonal presence of \*M. asterias\* in the receiver area. 96.7% of detections were at receivers just outside the Western Scheldt, and 97.4% of detections were from females. This indicates that the outer part of the Scheldt Estuary is a relevant habitat for females between April and November.

8 ADST were recovered, with two individuals (1 female, 1 male) logging data for over a year. Both tags logged depths between 0 and 20 m between June and October, and depths between 10 and 75 m between October and June. The changing depth range reflects the migration of the sharks into deeper waters during winter months. Continuous Wavelet Transform displays differences in periodic patterns between seasons and the two individuals, linking to resting or feeding behaviour. The results suggest that the female is resting during summer and feeding in a biweekly pattern in winter, and the male is continuously feeding.  
This study provides first details about seasonality in vertical movement behaviour of \*M. asterias\* and confirms its seasonal presence in the Western Scheldt. Further studies to investigate to potential sex specificity are recommended for the future

# Abstract

\*abstract (200 words) is conform with the summary but without detailed information about Methods and Results\*

\*\*currently: 198 words\*\*

The starry smooth-hound \*Mustelus asterias\* is widely distributed in the Northeast Atlantic, yet under increasing fishing pressure. To lay the grounds for future species management plans, information on its complex annual migration and residency behaviour is needed.

Fish movement is commonly studied with electronic tags, one novel technology being the Acoustic Data Storage Tag (ADST). It can be detected by acoustic receivers and additionally logs temperature and water depth in predefined intervals.

This study characterises the migration and residency of \*M. asterias\* in the North Sea regarding season and sex. 30 \*M. asterias\* were equipped with ADST in the Scheldt Estuary in 2018 and 2019.

Acoustic detections of 18 individuals in the Western Scheldt estuary between July 2018 and July 2020 suggest seasonal presence of females just outside of the Western Scheldt between April and October.  
Spectral analysis of the depth logs of two individuals logging for over a year reveals feeding behaviour of the male throughout most of the year. The female shark primarily rests on the seafloor during summer and feeds in a biweekly rhythm during winter.

This study presents the first detailed insights into vertical movement behaviour differences between seasons and individuals of \*M. asterias\*.

160 acoustic receivers that can detect ADST are currently installed in the Scheldt Estuary and the Belgian Part of the North Sea (BPNS) as part of the European Tracking Network.

In 2018 and 2019, 30 adult \*M. asterias\* (19 females, 11 males) were equipped with ADST-V13TP (Innovasea, 518 days estimated battery life) in the Scheldt Estuary. 18 individuals (14 females and 4 males) were detected 10940 times by the acoustic receivers between July 2018 and July 2020.

All detections were between April and November, suggesting seasonal presence of \*M. asterias\* in the receiver area. 96.7% of detections were at receivers just outside the Western Scheldt, and 97.4% of detections were from females. This indicates that the outer part of the Scheldt Estuary is a relevant habitat for females between April and November.

8 ADST were recovered, with two individuals (1 female, 1 male) logging data for over a year. Both tags logged depths between 0 and 20 m between June and October, and depths between 10 and 75 m between October and June. The changing depth range reflects the migration of the sharks into deeper waters during winter months. Continuous Wavelet Transform displays differences in periodic patterns between seasons and the two individuals, linking to resting or feeding behaviour. The results suggest that the female is resting during summer and feeding in a biweekly pattern in winter, and the male is continuously feeding.  
This study provides first details about seasonality in vertical movement behaviour of \*M. asterias\* and confirms its seasonal presence in the Western Scheldt.

Acknowledgements

This work was supported by the Research Foundation Flanders (FWO) as part of the Belgian contribution to LifeWatch. I am indebted to everyone involved in the tagging of the 30 starry smooth-hounds in 2018 and 2019 without whom this study would not have been possible. My gratitude extends to everyone involved in the maintenance of the acoustic receiver network involved in this study. Furthermore, I appreciate the effort by everyone involved in the return of the tags, enabling me to study the annual vertical movement of the starry smooth-hounds in the first place. I am thankful to the Flemish Marine Institute (VLIZ) for having granted me the opportunity to conduct my master thesis with them, and the IMBRSea coordinators for their continuous effort to make this study programme happen.

I wish to express my heartfelt thanks to my promotors Jan Reubens and Niels Brevé, and my supervisor Carlota Muñiz. Thank you Jan, for providing me with constructive and valuable feedback, thank you Niels for your invaluable input on the starry smooth-hound, and thank you Carlota for guiding me and looking after me when I was a bit stuck.  
Furthermore, I am grateful for having been able to go out into the Belgian Part of the North Sea for receiver maintenance work, this experience gave me valuable insights into the practicalities behind the receiver network.  
My sincere appreciation goes to Pieterjan Verhelst, for taking me along the Twaite Shad tagging campaign and the car conversations about fish migrations and fishermen’s knowledge. Thank you to Jolien Goossens for carrying out the geolocation modelling of the returned tags which provided an important base for me to follow up on.  
I furthermore wish to thank my IMBRSea study mates for productive co-working sessions and emotional support throughout the thesis. My thesis would not have been the same without all the warmhearted colleagues at VLIZ, thank you all for this extraordinary time in Gent and Ostend.   
My eternal gratitude goes to the people that I deeply care for, especially Silvi and Tobi, for emotional support and understanding during this intense period.  
And lastly, endless thanks to my parents for being there and supporting me no matter what.

* Jan: providing constructive and valuable feedback
* Carlota: looking after me
* Niels: invaluable insights into the starry smooth-hound
* People tagging the sharks (Pieterjan e.g.)
* Pieterjan for talks about fishermen
* VLIZ
* My study mates: coworking sessions and support
* Vliz colleagues: social welcome and making me feel part of the group
* IMBRSea programme and its coordinators: sometimes underappreciated but essential work to give us students the opportunity to study this programme
* People that I care for: emotional support, especially Silvi and Tobi
* My parents; being there for me, proofreading

U.S. Naval Observatory. Earth’s Seasons - Equinoxes, Solstices, Perihelion, and Aphelion. Astronomical Applications Department 2023. https://aa.usno.navy.mil/data/Earth\_Seasons (accessed May 31, 2023).

# 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

A picture containing map, text

Description automatically generated

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

A picture containing text, line, number, plot

Description automatically generated

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

A picture containing diagram, line, screenshot, plot

Description automatically generated

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

A picture containing text, map, diagram, atlas

Description automatically generated

Figure : Map for reference about station locations.

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

A picture containing line, diagram, plot, screenshot

Description automatically generated

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.

A picture containing diagram, line, plot, screenshot

Description automatically generated

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

A picture containing line, plot

Description automatically generated

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

A picture containing line, plot, diagram

Description automatically generated

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

A picture containing text, line, diagram, font

Description automatically generated

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)

A picture containing text, line, font, receipt

Description automatically generated

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

A picture containing text, line, diagram, parallel

Description automatically generatedA screenshot of a computer code

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)

A picture containing text, font, handwriting, line

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)

A picture containing text, diagram, line, font

Description automatically generated

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

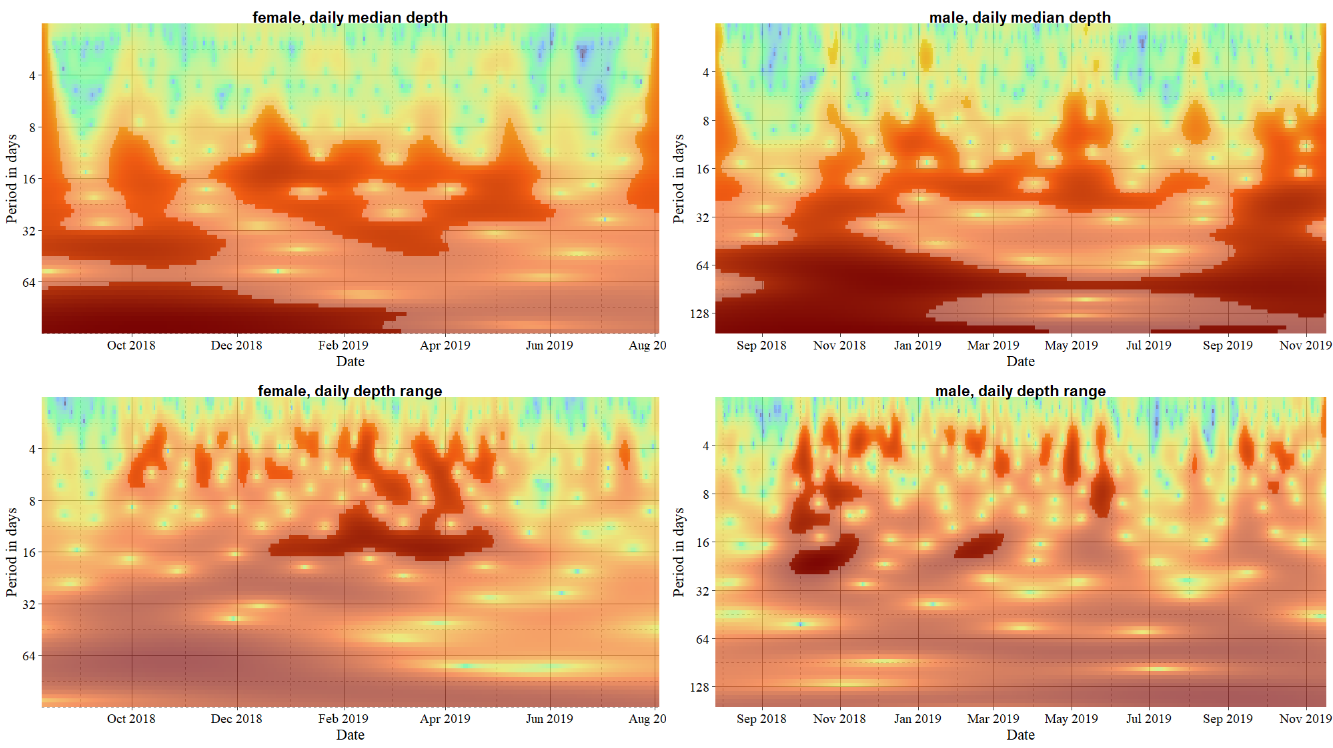


Figure : Wavelet scalograms from daily summary statistics. Left: female (tag 308), right: male (tag 321), top: daily median depth, bottom: daily depth range

Horizontal Distance (from the geolocation model output)

A picture containing text, line, plot, font

Description automatically generated

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

A picture containing text, screenshot, plot

Description automatically generated

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 {#sec-disc-seasonalpresencefemales}

There are no acoustic detections at all [cf. @fig-abacus] between November and April in all years with acoustic detections (2018-2020). This suggests 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 to especially relevant periods for the species in the area and it is recommended to study the seasonal presence of \*M. asterias\* in the Western Scheldt with greater detail in the future.

According to the acoustic detections, a hotspot of seasonal presence of mature \*M. asterias\* females is around 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 should be subject of further studies.

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; @smukall\_2019; @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 in the WS2 array throughout the whole study period from 2018 to 2020) 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 [@breve\_2016], 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].

<!--which was also. Substantially decreased presence of \*M. asterias\* in the Dutch delta was linked to water temperature < 13 °C [@breve\_2016]. Since water temperatures are a main predictor of elasmobranch occurrence [@martin\_2010]. 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 and sex-specific vertical movement patterns {#sec-disc-dst-movementpatterns}

*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

Overall, cyclidity can be observed for both the female and the male shark logging data for more than a year. The autocorrelograms [@fig-acf] show similar seasonal patterns with an autocorrelation of zero at lags of 81 and 264 days for the female, and 75 and 256 days for the male. The lags correspond to roughly 3 and 9 months, suggesting a change of vertical movement behavior at these time scales. Global minima lie at lags of 170 and 138 days for female and male, respectively. These lags roughly correspond to 5 months and indicate that vertical behaviour is anti-correlated within this time scale, further underlining the observation of higher vertical activity and the use of deeper waters during winter and a contrary behaviour with low vertical activity use of shallow waters during summer. Local autocorrelation maxima lie at 300 and 345 days for female and male, respectively. This corresponds to 10-12 months and points towards a yearly cyclicity for both the male and the female shark.

In general, owing 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.

#### #### Summer

From both recovered DSTs that logged data for over a year, the daily vertical range and median depth are shallower in summer (June – September, 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 (December – March).

<!-- 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. Both in the summer of 2018 and 2019, 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). In 2018, there are some periodicities of 24 h (indicated by yellow colours) as opposed to 2019, where the power of the 24 h period is below zero. This could be an indicator of the biannual reproductive cycle [with females feeding when they are not pregnant, and they stop feeding during the migration to parturition grounds and parturition itself, @michael\_2006, p. 23] but this requires further investigation in the future. The 12 h periodicity, however, is the most prevalent one in both summer for the female and thus 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 suggests 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 {#sec-disc-wintermig}

From September 25 for the female and October 21 for the male, the daily median 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 in 2018 and 2019. Since this tag logged for 485 days, the migration into the winter habitat was recorded for two years. The start date of the potential winter migration in 2019 differs to the one in 2018 by 10 days. The autocorrelation of the depthlog of tag 321 has a local maximum of 345 days [see @fig-acf-2] which further reflects the almost perfect yearly cyclicity of tag 321.

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 potential resting behaviour after the completion of the migration was not further assessed at this point and could be subject of future studies.

<!-- Furthermore, the male shark (tag 321) logged longer than the female, and there the hourly wavelet scalogram shows high prevalence of periods from 4 h to 64 h in the first week of October 2019. A stark depth increase can also be seen in the daily median depth [@fig-dstsum-2], indicating the individual’s migration to its winter habitat. -->

#### #### 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 @sec-results-moonphases and is discussed in the following.

##### \*\*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.

#### #### Migration into summer habitat {#sec-disc-summermig}

In spring, roughly between April and May, the daily median depth gets shallower in a stepwise manner for both individuals which potentially reflects 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 [as suggested by @breve\_2016 and firstly reported by @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 few weeks. From the wavelet scalograms of the raw depthlog [@fig-waveletresults308-1 and @ fig-waveletresults321-1] the time of potential migration into the summer 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, there is no clearly visible change in periodicity patterns between winter months up until March and the months of April and May, during which the daily median depth decreases stepwise for the female shark.

During April 2019, the male shark does not show any prevalent periodicity patterns in the wavelet scalogram at hourly scale [@ fig-waveletresults321-1]. The month of May 2019, however, shows prevalent periodicities between 12 and 64 h, potentially indicating migration behaviour. There is decreased vertical activity compared to the winter months from mid-May onwards for the female and from June onwards for the male, indicating that the individuals might have arrived at their summer habitat by then.

At this point, knowledge about the exact spectral signature of \*M. asterias\* migration behaviour is lacking and it is suggested that this should be further studied. Moreover, 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 investigations.

* 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?)

## **## Gained ecological knowledge on \*M. asterias\* in the context about \*M. asterias\* and related species**

\*Mustelus asterias\* is a common species in the North Sea and the English Channel, both of which areas experience high anthropogenic impact. Since knowledge about the species and its relatives is still limited, the following section aims to give a brief overview of how the knowledge gathered in this study fits into already existing ecological knowledge about \*M. asterias\* and related species.

Comparisons about reproductive behaviour must be made cautiously since not all members of the Genus \*Mustelus\* exhibit aplacental viviparity like \*M. asterias\*. \*M. asterias\*, for instance, was often mistaken for the common smooth-hound \*M. mustelus\* before the development of a simple genetic method to distinguish the two species [@farrell\_2009], yet this relative is placentally viviparous [@dasilva\_2018]. The gummy shark \*M. antarcticus\* inhabits Australian waters and exhibits matrotrophic aplacental viviparity like \*M. asterias\*, making it well comparable. Moreover, asynchronous breeding cycles (of one and two years) related to different locations were uncovered for \*M. antarcticus\* [@walker\_2007]. This behaviour is also known to occur in Squalid sharks [@braccini\_2006], but there is no evidence that \*M. asterias\* exhibits different breeding cycle lengths.

Nevertheless, the reproductive biology of \*M. asterias\* is highly complex, involving embryo asynchronism, for instance (i.e., pups with different developmental stages, potentially resulting from sperm storage and selective fertilization by the females, @farrell\_2010a). While an in-depth stock assessment has already been carried out for \*M. antarcticus\* by @pribac\_2005, this is still lacking for \*M. asterias\* and should be done [@mccullyphillips\_2015].

Annual migration behaviour has not been investigated in depth for many \*Mustelus\* species. In fact, the gummy shark \*M. antarcticus\* is reported to be less mobile than other elasmobranchs in the area of Western Australia [according to a three-year acoustic monitoring study involving 100 tagged \*M. antarcticus\*, @braccini\_2017], but still able to cover distances of > 60 km per day, and overall distances of almost 1000 km. The narrownose smooth-hound shark \*Mustelus schmitti\*, an aplacentally viviparious relative of \*M. asterias\* that inhabits waters in the south-west Atlantic, is thought to exhibit similar seasonal migration patterns as \*M. asterias\*. @elisio\_2019 argues that although migration patterns of \*M. schmitti\* are still unknown, large-sized individuals are increasingly abundant in deeper waters during autumn and winter [@cortes\_2011], suggesting a seasonal migration to shallower waters. The same study reported parturition events of \*M. schmitti\* in coastal waters during spring and summer, following warming temperatures above 16 °C. These findings align well with conclusions from @breve\_2016 that reported decreased presence of \*M. asterias\* for temperatures < 13°C.

Compare findings of this study to Griffiths 2020, breve 2016

Overall, the results of the present study go in line with already gathered knowledge on \*M. asterias\*. The geolocation model results suggest that the male shark spends the winters in waters north of the Scheldt Estuary and the female goes into the English Channel, as assumed by @breve\_2016 and @griffiths\_2020. Different overwintering spots for the female and the male shark are further supported by the presumable stronger effect of moon phases and tidal currents on the vertical activity of the female \*M. asterias\*, potentially sheltering from the intense tidal currents in the English Channel. The present study, however, only involved year-long DST logs from two individuals, so any inferences from this data have to be taken cautiously.  
The high return rate (`r round((sharks\_returned / sharks\_detected) \* 100)` %) of individuals as shown by the acoustic detections in the acoustic receiver array further underlines philopatric behaviour in regard to the species’ summer habitat, the Southern North Sea [@griffiths\_2020].

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

For the present study, a novel type of electronic combination tag was utilized, combining acoustic detections with data storage logs. For maximum data overlap, the tag should both be acoustically detected and retrieved (to access the DST part). This was the case for 3 out of the 30 tags deployed in this study. Tag 319 was detected 7 times, and the individual (f) died 19 days post-release, tag 295 was detected 21 times and the shark (m) died 30 days post-release, and tag 308 was detected 2067 times and was acoustically detected last 366 days post-release. Thus, only tag (tag 308) shows sufficient data overlap. Its dephlog together with acoustic detections in @fig-adst308 shows that the female was detected at the Birkenfels receiver station (which is in the BPNS) 63 days after the DST depthlog stopped. This suggests the departure of the individual from the BPNS and the Scheldt Estuary and aligns almost perfectly with the depthlog of that time one year before, where the female went to waters deeper than 25 m from October 06, 2018, onwards. While the annual cyclicity for the male could already be shown from its depthlog since it logged well over a year [see @sec-disc-wintermig], the detectionof tag 308 at the Birkenfels station points towards an almost perfect annual cyclicity for this individual, too.

Generally, ADST are a well-suited tracking technology for \*M. asterias\*, owing to their seasonally differing resident and migratory behaviour. It allows for gaining high-resolution presence/absence data within the areas of receiver networks and insights about the vertical movement of an individual independent of the acoustic detections, given that the tag is retrieved. Moreover, the acoustic detections provide punctual ground truth for geolocation modelling, which is especially helpful in highly mixed areas with homogeneous bathymetry like the Scheldt Estuary. Such areas generally result in limited reliability of geolocation models as the models cannot make out a definite position by depth and temperature if these variables are roughly constant throughout the area.

* 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.

### ### Limits and biases of the telemetry methods used

In the following section, shortcomings of the telemetry technologies and the resulting datasets will be discussed.

### ### Tag recoveries and possible tagging effects {#sec-disc-tagging-effects}

Of 30 deployed ADST, 9 were recovered so far, with data availability at the time of writing of 8 ADST. Out of those, 6 \*M. asterias\* died within the first month post-release.  
There are numerous factors that potentially contribute to a negative effect of the tagging procedure.

For instance, the choice of tag to implant must be made considering the animal’s body mass. Generally, it is advised that the tag should not exceed 10 % of the individuals’s body mass [@wagner\_2011]. In the present study, weight was recorded for 17 out of 30 individuals tagged. Out of those, the smallest individual weighed 900 g, resulting in a tag-to-bodymass ratio of 1.4 %. However, little information on tagging effects on elasmobranchs is available. @smukall\_2019 report the non-lethal recovery of an acoustic tag 13 years post-release, implanted into a female Lemon shark (\*Negaprion brevirostris\*) at 119 cm TL. Thus, it does not seem likely that the tag’s weight had a severe negative influence on the survival of the tagged individuals.  
Other possible factors include insufficient asepsis of surgery tools and the tags itself, or negative physiological responses due to insufficient handling [@smukall\_2014]. This includes too much time outside of the water, injuries from the fishing method (hook and line, in this case), or the tag implantation taking too long. Why the 6 \*M. asterias\* individuals died cannot be answered at this point, but it is suggested to always ensure optimal handling, choice of tag, and surgery procedures to ensure good survival conditions of the tagged animals.  
Death due to predation by an endothermic mammal predator such as the grey seal can be excluded, because the temperature did not substantially rise (to around 38 °C, @austin\_2006) prior to the animals’ deaths (all raw depth an temperature logs are shown in Annex -@sec-annexdst\_raw. Generally, the temperature logs of the short term DST appear erroneous, note for example that the temperature remains 21.2 °C for tag 319 between August 4 and 12, 2018. The possibility of predation by an ectothermic predator cannot be ruled out at this point, since temperature cannot provide any relevant insights but instead the depthlog would show extraordinary vertical movement [see @seitz\_2019 for examples of predation by endothermic versus ectothermic predators]. The possibility of predation by an ectothermic animal such as the blue shark \*Prionace glauce\* should be further investigated.

% - 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

Essentially, two type of dataset were used for study: Firstly, the acoustic detections of the tagged sharks, and secondly, the DST logs from recovered tags

<!-- Both datasets entail limitations which will be briefly discussed here. -->

The 10,940 acoustic detections of 18 \*M. asterias\* individuals over a period of roughly two years are already a relevant dataset to start with, but more tagging effort and thus more acoustic detections are needed to gain further insights into the presence of the species in the Scheldt Estuary. For comparison, @hereu\_2023 tagged 33 European seabass (\*Dicentrarchus labrax\*), a seasonally migratory fish [@pawson\_2007], and had 493.817 acoustic detections over roughly 2 years in an acoustic receiver network comprised of around 100 receivers [@aspillaga\_2017].

Moreover, the gate-like receiver setup in the Western Scheldt is not ideal to study horizontal distribution but rather serves to detect animals that enter or leave the river Scheldt [@reubens\_2019]. If possible, additional receiver could be placed along the coast between Dishoek and Zoetelande to further resolve the seasonal presence of adult females in the area and potentially gain information on pupping grounds.

The availability of only long term DST logs (that is, a log with more than a year of data) poses the greatest limit on the archival dataset. More logs showing the annual migration should be analysed in the future to assess whether the sex-specific patterns described in this study are due to variation between individuals or due to the animal’s sex.

The short term DST logs were not further investigated in the present study since altered behaviour resulting from the tagging procedure could not be excluded. However, investigating the short term DST logs could be valuable to assess in the future.  
An additional restriction of the archival data is the limit of the depth sensor of 68 m. Since the female shark swam deeper than that limit between October and December, 2018, limited inferences can be made from the female’s depthlog during that period and the current results from the geolocation modelling are imprecise.

• 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 data collection but instead was purely focused on the analysis of the acoustic detection and data storage tag datasets, 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 looked 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 argued in @sec-disc-acousticdetections.

### #### Autocorrelation

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

Autocorrelation analysis allows for a simplistic description of scales of patterns found in time series. It is a helpful exploratory tool to get an overview of the dataset [@dray\_2010] which can provide the base for the detection of behavioural switches [@gurarie\_2016]. Although not very common in the analysis of ecological time series, insights on the seasonal scale of vertical movement patterns from this study show its potential.

<!-- The characteristics of the autocorrelations of the two long term depthlogs in the present study show similar patterns in time series between the female shark (tag 308) and the male shark (tag 321), indicating that their daily median depth is very similar in time periods of 3 - 5 weeks (that is, with lags below 24 to 35 days). Interestingly, both individuals show turning points in their autocorrelation (i.e., the autocorrelation goes from positive to negative values) at similar lag values, suggesting similar seasonal depth patterns. Furthermore, the local autocorrelation maximum is at similar lag days of about a year for both individuals, indicating an annual pattern in vertical behaviour. It does not allow for an in-depth investigation of behavioural switches and is generally regarded as a first-hand exploratory analysis. Autocorrelation is a very basic exploratory analysis method used, amongst others, to determine the scale of patterns in time series data. In the present study an annual pattern for both long term DST could be seen [see @sec-resacf and @ sec-disc-dst-movementpatterns], as both for tag 308 and 321 the autocorrelation reached a local maximum at a lag of around 10 – 12 months. Going further, the minimum of the autocorrelation occurs in winter. Thus, autocorrelation is a useful method to check if the assumptions about general vertical patterns (in the present case, the same vertical behaviour (resulting in a local autocorrelation maximum) every summer and a different behaviour (resulting in a local minimum) in winter). Potentially interesting are the points at which the autocorrelation is 0. This is the case at a lag (\*insert exact lags and dates here\*). It might be indicative of a behavioural switch. But this would only hold true in the case of behaviours that can be distinguishable from the depthlog. -->

While autocorrelation might not be the most resultful exploratory analysis it can be a helpful auxiliary tool to 1) explore the depth time series data and 2) potentially confirm identified periods with occurring behavioural switches.

<!-- overlay identified change periods with diff. step percentages and do `rgrid.arrange(p\_acf\_308, p\_308\_ribbon\_rulsif\_allpercent, ncol = 1)` and see where autocorrelation = 0 and the identified change periods match. -->

### ### Wavelet Analysis

Conducting a continuous wavelet transform (CWT) and thereby resolving prevalent periodicities in the time domain proved to be a main analysis tool in this study. Furthermore, performing CWT both 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. Wavelet analysis is no ubiquitous analysis tool in movement ecology but has been employed in the past [@wittemyer\_2008; @zhang\_2020].  
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 an 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

This study presents the first in-depth investigation of both the seasonality of vertical movement behaviour and presence of \*M. asterias\* in the Western Scheldt. Adding to already existing knowledge, the seasonal presence of mostly adult female starry smooth-hounds could be confirmed, proving the importance of the Western Scheldt as a summer habitat and further indicating a potential pupping ground (presumably around the receiver station OG10. Moreover, the high return rates provide further evidence for philopatric behaviour of the species. Although males and females most likely overwinter in different areas [@breve\_2016; @griffiths\_2020], their seasonal vertical movement behaviour appears to be similar (involving generally less vertical activity during summer and higher vertical activity during winter), according to the two DST tags that were subject of this study. During summers, however, the female showed primarily resting behaviour while the male exhibited both resting and feeding behaviour, indicating sex-specificity in behavioural states on a within-season scale. During winter, the female’s (and to a lesser extent, the male’s) vertical activity is potentially influenced by the moon phase which might be linked to the intensity of tidal currents.

Thus, this study could gain new insights into the seasonal distribution and potential sex-specificity of horizontal and vertical movement behaviour of \*Mustelus asterias\*. There still is, however, a substantial knowledge gap about the effects of sex and life stage on the species’ distribution [@griffiths\_2020] and to be able to establish a successful species management plan in the future, further studies are needed [@mccullyphillips\_2015; @breve\_2016; @breve\_2020, @griffiths\_2020].

* 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

## ## Tagging studies involving \*M. asterias\*

As discussed in @sec-disc-seasonalpresencefemales, an insightful addition to future tagging studies involving adult \*M. asterias\* would be to assess upon sampling if a female is gravid or not. This could be done either through ultrasonography or the use of sex steroid hormones [@awruch\_2014; @smukall\_2019; @anderson\_2018; @fujinami\_2020; @fujinami\_2021]. A new tagging technology was launched recently: The Birth Alert Tag [BAT, @sulikowski\_2023], which is, however, only advised to be used on “large sharks”. If smaller BATs are developed in the future, this might be a suitable tag to use on \*M. asterias\*.  
In addition, the placement of an acoustic receiver off the coast of Zoetelande might give further insights into possible seasonal \*M. asterias\* in summer, as described by fishermen.  
If possible, DST with a wider depth range should be utilized for future studies, since evidence of \*M. asterias\* swimming in deeper waters (> 100 m depth) than previously thought is accumulating [@ices\_2019; @griffiths\_2020].

Generally, the effect of the implantation of tags on the sharks should be investigated. Since female \*M. asterias\* have been previously reported to abort and expel embryos when caught [@farrell\_2010a], special attention should be drawn to the tagging effect on pregnant females, especially when intending to study their pupping behaviour.

* 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

## ## Analysis of data storage tag logs

The adequate analysis of DST logs and the development of well-performing geolocation models remains a challenge.   
While the input of behavioural states (i.e., high or low vertical activity, or residential versus migrating behaviour) would provide improved input for a geolocation model, segmenting the depthlog in different behavioural states is not trivial. Instead, a first improvement for the geolocation model could be the addition of a simple boundary condition that reflects the demersal lifestyle of \*M. asterias\*. This boundary condition entails that the maximum depth logged by the tag each day (given that the resolution of the geolocation model is in the unit of days) is equal to the maximum depth of the seafloor at the location of the shark. This would prevent model outputs that estimate the individual’s position on a day at locations with substantially deeper seafloor depth than the shark’s depthlog has recorded that day.

Furthermore, wavelet analysis proved to be a helpful tool for assessing the seasonal changes in spectral composition of the depth signal for both individuals. This technique should definitely be further taken into account in the future, for instance regarding the segmentation of the depthlog into different behavioural states [@soleymani\_2017]. Since the implementation of simple CWT in this study is still an exploratory technique it should be investigated how it could be quantified in the future. If different behavioural states, for example resting, feeding and migrating can be linked to specific spectral signatures (i.e., a 12h period for resting, a 24h period for feeding and high prevalence of periods from 4h to 64 h for migrating), then wavelet coherence could be a next analysis step. This analysis assesses the similarity of two wavelet scalograms. Conducting wavelet coherence between the raw depthlogs of the sharks and characteristic spectral signatures of different behaviours could quantify the presence of different behavioural states in the future. Several methods to quantify behavioural states exist already [cf. @pedersen\_2008; @heerah\_2017] but there is not one generic method that works for all species equally. Thus, it would be valuable to test the method suggested here and compare it to outputs from already existing methods. This would be a next step towards improving the geolocation modelling for \*M. asterias\* and with that our knowledge and understanding of the species.