Answers to RC 2

Overview: *The main finding of this study is that turbulent ship wakes can reach deeper than the previously observed values, however, no physical explanation or discussion is provided. It is expected that ship specifications and speeds determine ship wake depths, so the authors should be able to discuss further based on the available ship information.*

We acknowledge the comment to relate the wake depth and longevity to another parameter than ship type, and therefore suggest a revision of the result section. It is beyond the scope of this paper to investigate the dependence between various non-dimensional parameters, which would be the most physically justified thing to do. However, we expect that the wake size to a large degree depends on the force or power put into the water by the propeller. We do not have data on these parameters, but we do expect that both the force and the power depend on the dimensions and speed of the vessel though water. The drag force on the ship is one of the possible resistances the ship is exposed to.

We therefore propose exchanging the current figures 5 and 6, to Figure 1 and Figure 3 and/or Figure 2 and Figure 4 below. The new figures show the wake depth and longevity in relation to force (F), calculated as $\rho * ship\ width * ship\ draught * ship\ speed^2$ [kg m s^{-2}], with seawater density (ρ) equal to 1025 kg m^{-3}. This parameter is proportional to ship drag and will relate the wake depth and longevity to vessel size and speed, which we agree are parameters expected to have an impact on the formation of the turbulent wake.

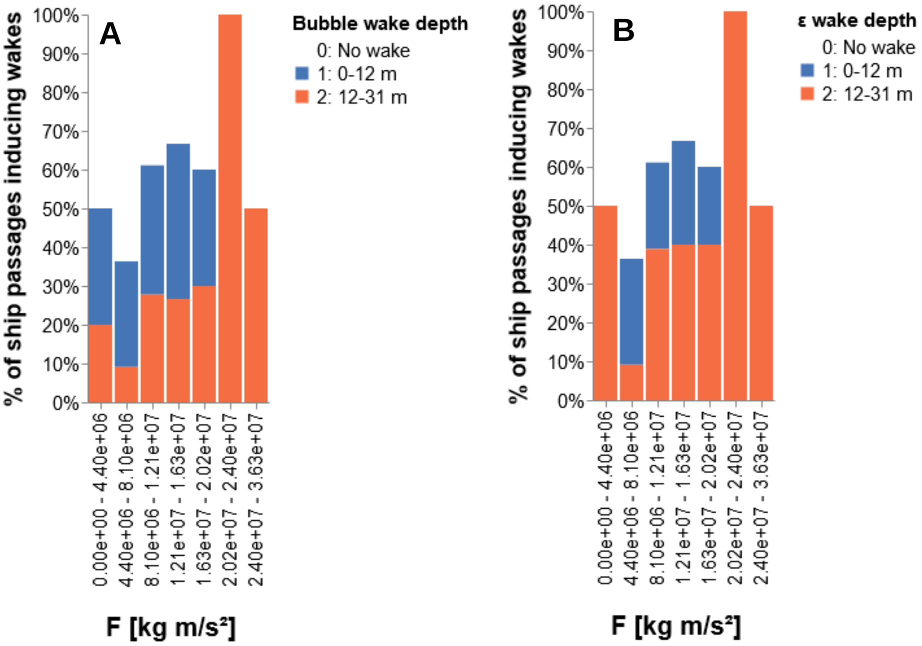

*Figure 1. Maximum wake depth for the bubble wake (a) and dissipation rate of turbulent kinetic energy (ε) wake (b), for the wakes induced by ships passing at 0-3 ship widths from the instrument. The x-axis shows the force (F) of the vessel in Newton, calculated as ρ*ship width*ship draught*ship speed^2. Wake depths within the range presented in previous studies are shown in blue and wakes deeper than previously reported are shown in orange.*

Figure 1 and Figure 2 shows the maximum wake depth for the bubble wake and dissipation rate of turbulent kinetic energy (ε) wake. The difference between the figures is Figure 1 only shows the ships passing within 0-3 ship widths from the instrument (roughly corresponding to 75 m), whereas Figure 2 shows all the passages in the dataset. As a majority of the induced wakes are from ships passing within 0-3 ships widths from the instrument, we propose to limit the graphical presentation of the dataset to this part of the dataset. We can see a clear cut-off in the percentage of detected wakes at 3 ship widths. Hence, as we are currently not able to correct for the uncertainties introduced by the distance factor (see discussion in manuscript for further details), we argue that the closer passages give a better representation of the actual temporal and spatial scales of the turbulent wake, than including the entire dataset. Nevertheless, we propose presenting statistics for both the entire dataset and the passages within 3 ship widths of the instrument.

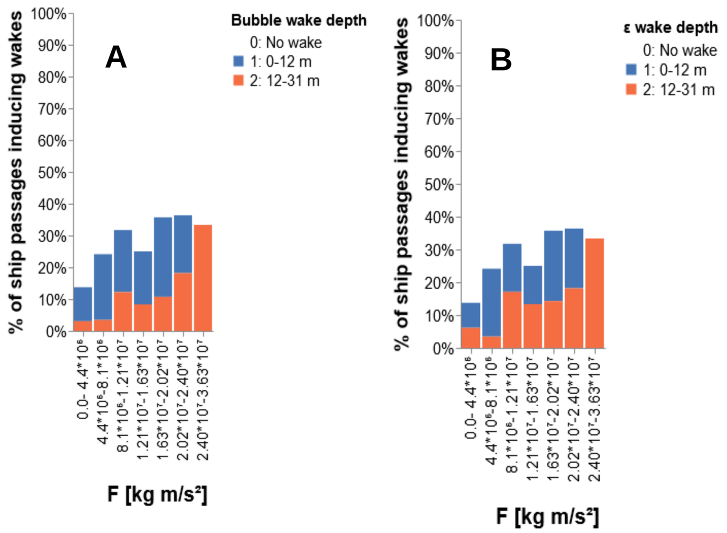

*Figure 2. Maximum wake depth for the bubble wake (a) and dissipation rate of turbulent kinetic energy (ε) wake (b), for all single passages. The x-axis shows the force (F) of the vessel in Newton, calculated as seawater density*ship width*ship draught*ship speed^2. Wake depths within the range presented in previous studies are shown in blue and wakes deeper than previously reported are shown in orange.*

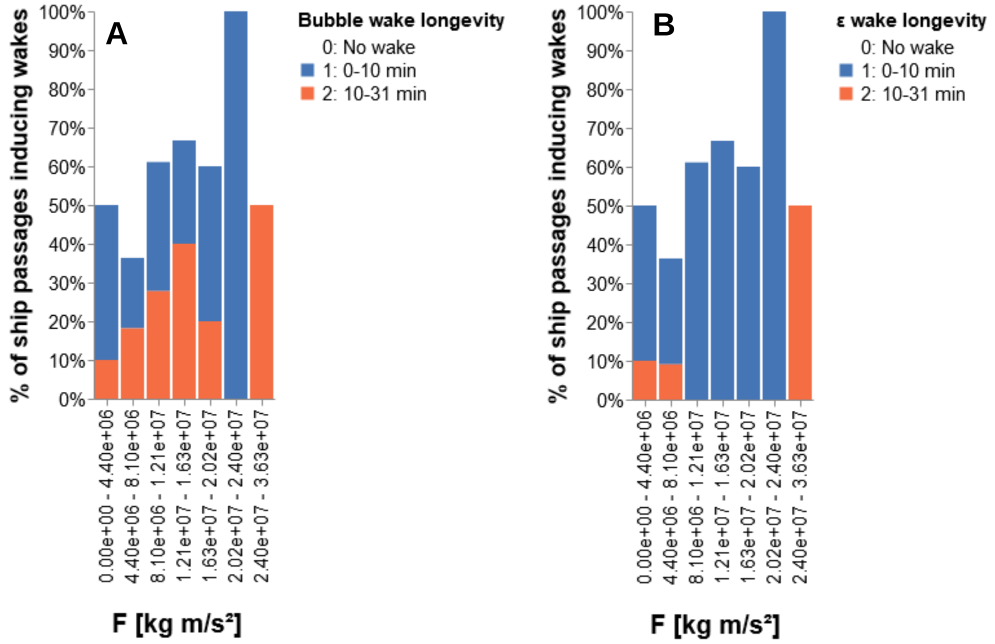

*Figure 3. Wake longevity in minutes for the bubble wake (a) and dissipation rate of turbulent kinetic energy (ε) wake (b), for the wakes induced by ships passing at 0-3 ship widths from the instrument. The x-axis shows the force (F) of the vessel in Newton, calculated as seawater density*ship width*ship draught*ship speed^2. Wake temporal longevities < 10 min are shown in blue and wake longevities 10–30 min are shown in orange.*

Similarly, Figure 3 and Figure 4 and shows wake longevity for the bubble wake and ε wake, for the ships passing within 0-3 ship widths from the instrument and all single passages in the dataset, respectively. We suggest the same presentation and statistics as for the maximum wake depth parameter. For both wake depth and longevity, we suggest including the figure with the closest passages in the manuscript, and the figure for the entire dataset to be added to a supplementary info. If requested, the supplementary info can also include a figure showing the wake detection for different distance categories, to illustrate the wake detection cut-off at 3 ship widths (Figure 5).

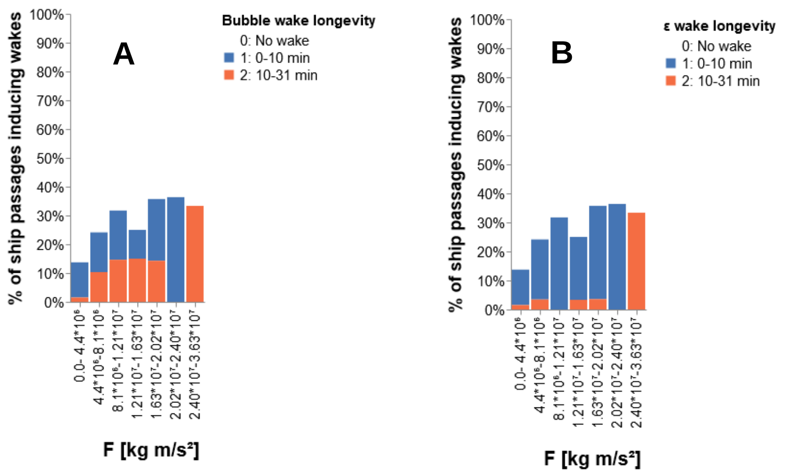

*Figure 4. Wake longevity in minutes for the bubble wake (a) and dissipation rate of turbulent kinetic energy (ε) wake (b), for all single passages. The x-axis shows the force (F) of the vessel in Newton, calculated as seawater density*ship width*ship draught*ship speed^2. Wake temporal longevities < 10 min are shown in blue and wake longevities 10–30 min are shown in orange.*

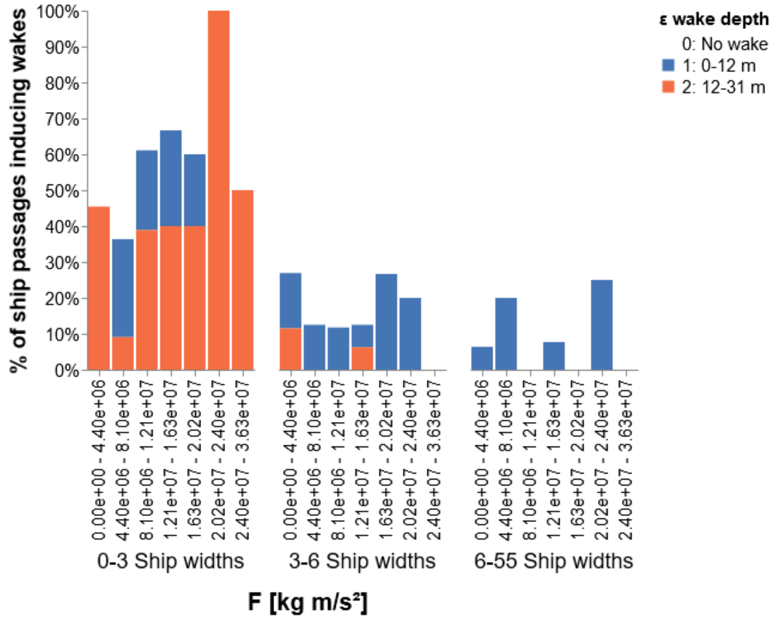

*Figure 5. Maximum wake depth for the dissipation rate of turbulent kinetic energy (ε) wake. The data is presented for three different categories of passing distances: 0-3, 3-6, and 6-55 ship widths from the instrument. For each distance category, the x-axis shows the force (F) of the vessel in Newton, calculated as ρ*ship width*ship draught*ship speed^2. Wake depths within the range presented in previous studies are shown in blue and wakes deeper than previously reported are shown in orange. Not the clear cut-off in detected wakes at passing distances > 3 ship widths.*

In addition to the change in figures, we also propose a change to table 2 and 3 in the manuscript. We will remove the ship type category statistics and instead include statistics for the close passage category (0-3 ship widths) (Table 1). As mentioned above, the double wakes will not be included in the figures, as we cannot determine which vessel that induced the wake, and thus lack the necessary vessel information to do the calculations. However, we argue that it is relevant to include these wakes in the statistical analysis, as the double category constitutes 28 % of the detected wakes. The aim of the paper is to describe the temporal and spatial scales of the turbulent wake, and the double passages are one type of wakes that frequently occur in the dataset. The inability to include them in the figure is not related to any uncertainty of the wake measurement and should therefore be included in the overall analysis.

Table 1. Mean, median, first quartile (Q25), third quartile (Q75), standard deviation (std), minimum value, and maximum value for wake depth and longevity for the close wake passages (within 3 ship widths), the single wakes, the double wakes and for all wakes in the datset.

	Bubble wake depth [m]					**Bubble wake longevity [min]**					
	Mean	Median	Q25	Q75	Std	Mean	Median	Q25	Q75	Std	**n**
Close wakes	11.8	11.5	9.5	13.5	4.3	00:11:00	00:09:59	00:06:29	00:13:15	00:06:34	39
All wakes	10.3	9.5	7.5	12.5	4.1	00:10:14	00:08:00	00:05:29	00:13:29	00:06:29	69
All double	11.2	10.5	8.5	13.5	4.4	00:12:21	00:11:29	00:07:00	00:19:00	00:06:23	27
All	10.6	9.5	7.5	12.5	4.2	00:10:50	00:08:44	00:05:53	00:15:45	00:06:29	96
	ε wake depth [m]					**ε wake longevity [min]**					
	Mean	Median	Q25	Q75	Std	Mean	Median	Q25	Q75	Std	**n**
Close wakes	13.4	13.5	11.5	14.5	3.7	00:06:17	00:05:59	00:04:45	00:07:44	00:02:33	39
All wakes	11.8	11.5	9.5	13.5	3.9	00:06:22	00:05:59	00:04:59	00:07:59	00:02:41	69
All double	12.9	11.5	9.5	17.0	3.8	00:09:07	00:08:00	00:06:44	00:10:14	00:03:53	27
All	12.1	11.5	9.5	14.5	3.9	00:07:08	00:06:30	00:05:00	00:08:30	00:03:18	96

	Distance to instrument [m]					
	Mean	Median	Q25	Q75	Std	**n**
Close wakes	32	29	16	42	21	39
All wakes	64	46	26	101	51	69
All double	31	18	9	46	32	27
All	55	38	16	82	49	96

The change of figures and tables will naturally be accompanied with a revised description and analysis of the result. The main findings, the statistics for the entire dataset will still be the same, thus the main findings will not change. However, the statistics for the closest passages will have slightly deeper and longer wakes, compared to the entire dataset (Table 1). As we consider this part of the dataset more representative, this will only strengthen the overall argument that the temporal and spatial scales of ship wakes are large enough to take into account in areas with intense ship traffic. We also suggest using the median values from the close passage category for the calculations in the example in section 3.3 in the manuscript.

Regarding the general comment "*The main finding of this study is that turbulent ship wakes can reach deeper than the previously observed values, no physical explanation or discussion is provided*". In relation to the new figures in the revised result section, we will develop the discussion regarding possible physical explanations to the variation in wake depth and longevity. However, there are two main reason to why this was not extensively discussed in the submitted manuscript.

Firstly, the aim of the study is to describe the spatiotemporal characteristics of the turbulent ship wake, and not to fully explain the physical variation. Nevertheless, we fully agree with and acknowledge the potential of further analysis of this phenomenon. However, resolving all the parameters determining the characteristics and impact of ship-induced turbulent wakes, will require years of further studies. Therefore, there is a need for a first, more descriptive study, which will provide an understanding of the relevant scales and parameters to consider in future studies, as well as a well described methodology. However, we acknowledge that the aim can be made clearer, and we therefore suggest changing the title to: "*In situ* observations of turbulent ship wakes and their spatiotemporal extent". In addition, we will rephrase the last paragraph (lines 105–115) in the introduction, to further motivate and describe the aim of the paper.

Secondly, we did look at possible physical explanations to the variation in wake depth and longevity, but due to low explanatory power, these results were only briefly mentioned, but not included in the submitted manuscript. We agree that there is a need to expand this discussion in the manuscript, and we will do so by using the vessel-related data we have. If requested, we could also include figures relating wake depth and longevity to ship length, draught, width, and speed, (Figure 6), as a basis for this discussion. However, in that case we propose including them in the supplementary information.

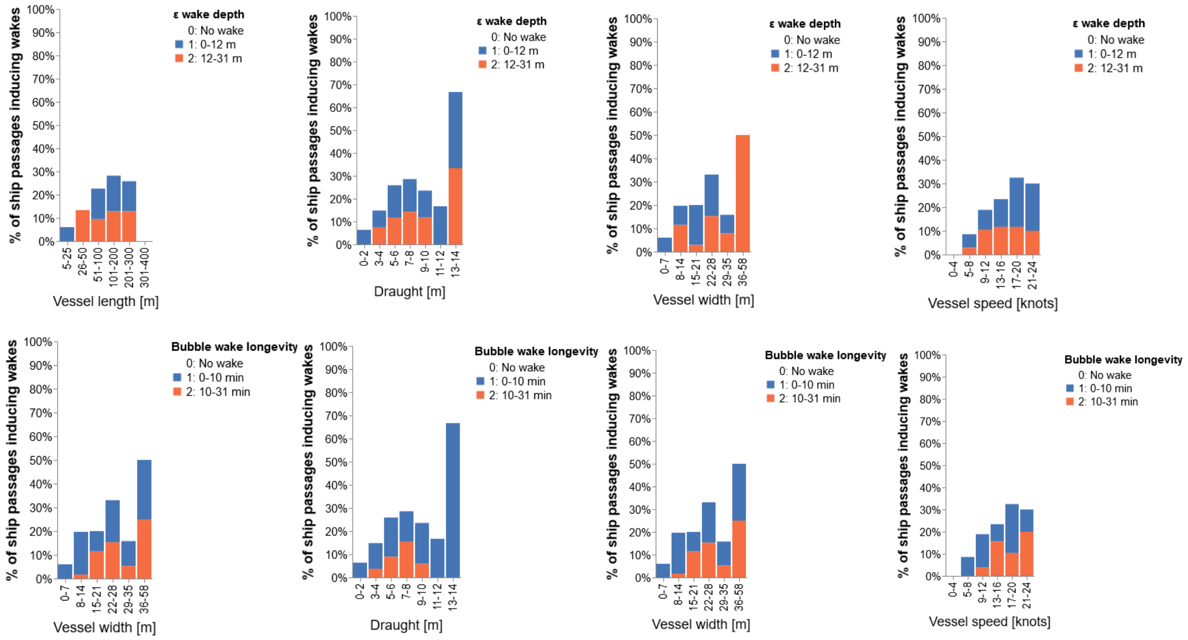

Figure 6. Example figures of how the vessel length, draught, width and speed relates to the ε maximum wake depth and bubble wake longevity, for all single passages in the dataset. Note that for all parameters but vessel speed, the categories with the highest values (rightmost bars) have very few passages (<10).

It is not clear why the authors chose two separate locations for the in-situ and remote sensing study. Is it possible to find satellite imagery for the in-situ measurement period?

We appreciate this very relevant comment. There is of course satellite imagery available for the *in-situ* study area as well, and we have retrieved it for the *in-situ* study period. However, the satellite passes only every 16th day, and during the study period there were no cloud-free images.

Regarding why we chose two different study areas all together, it was due to logistical reasons. The Bornholm study area was chosen as the ideal spot for the satellite study, as it one of the most intensely trafficked areas in the Baltic Sea. Initially, instruments were placed in the satellite study area, but due to unfortunate events they were lost. To have a better possibility to monitor the instrument, but still have an area with a lot of ship passages, we chose the Gothenburg harbour area for the second attempt of an *in-situ* study. The reason we still chose to keep the Bornholm are for the satellite study, was due to the more favourable weather conditions. A cloud free sky is needed for the satellite images to be usable, and since it only passes two times per month, the rainy

Gothenburg area was ill suited for the satellite study. We did not find this information suitable to include in the manuscript, but if requested we will motivate the choice of study area in more detail.

We suggest adding a comment in the manuscript, explaining the lack of cloud free satellite images from the *in-situ* study area and period, and the motivation for choosing the two different sites.

Also, vertical profiles should have been measured more frequently to see the effect of wakes on stratification and mixing.

We agree and acknowledge this as the main potential improvement of our observations, which we have also discussed in line 606-618. Furthermore, the long-term aim of our research is to be able to study and discuss the effect of wakes on stratification and mixing. However, the aim of the current study was to describe the spatiotemporal scales of the turbulent wake, and not resolving all the parameters determining the effect of wakes on stratification and mixing. As mention in a previous answer, we realise that the current title and aim, could give the impression that the paper is of a more explanatory nature. However, we consider the current amount of vertical profiles enough for the aim of this paper and suggest leaving the discussion regarding the effect of wakes on stratification and mixing for the next paper (where high-resolution profiling will be included).

To address this comment, we will clarify the aim of the paper as being mostly descriptive.

Specific comments:

Line 191: *Capitalize Python*

To address this comment, we will Capitalize Python on line 191.

Line 224: *Why 15%? Please justify.*

As stated in line 225-226, the wake area was manually defined using imagery of the echo amplitude and dissipation rate of turbulent kinetic energy. The exact value used for delimiting the wake region, was manually adjusted for each wake, using trial and error until the defined area sufficiently overlapped with the wake region in the image. Hence, the limit was chosen as the approximate value were noise was excluded but the wake region was included. However, this value was not decided upon in advance, but rather after the analysis it was clear that most of the values were approximately 15% higher compared to the daily/nightly mean.

To address this comment, we suggest clarifying that this value was not chosen in advance but was manually adjusted based on visual scrutiny of plotted figures, but that most values were ~15% higher than the daily/nightly mean.

Line 355-359: *Why do the bubble wakes look different from turbulence? Please discuss further.*

We acknowledge that this can be discussed further. The bubbles are an indication that surface water is mixed down at depth and has been mixed with the ambient water. They will remain there, or rise or collapse with time depending on size etc. The dissipation, on the other hand, is a measure of the turbulent motions in the water that mixes the water down. When the turbulence decays (due to dissipation) the dissipation also decays and dies out. But the bubbles may remain after that has happened.

The dissipation estimate is also influenced by neighbouring cells (equation 1), so the estimate may be deeper just due to the method used. I.e. if there is strong turbulence in one cell and none in the next, the method may still show some turbulence in the calm cell.

To address this comment, we suggest expanding the discussion regarding why the bubble wakes look different from turbulence, including the effect of bubble rise, collapse and retention, as well as possible biases due to the method used to estimate the dissipation.

Line 550-552: *This seems to be a negative result: the stratification was not affected by the wake. Remove this part. I suggest that the authors measure more vertical profiles in the study area and/or provide literature for more data to characterize general and unusual environmental conditions. 4 casts x 2 days are not enough.*

As mentioned in a previous comment, we agree and acknowledge that the amount of vertical profiles is too low to have an in-depth discussion regarding the effects of ship-induced vertical mixing on stratification. However, for the aim of this paper, we consider the current amount of profiles enough to describe the spatiotemporal scales of the turbulent wake.

However, regarding the comment related to the sentence above, we humbly disagree that it is a negative result. Turbulence will not be able to reach below the mixed layer, to 17.5 m depth, without mixing the water. Thus, we find it highly unlikely that the thermal stratification at 5 m was present within the wake. This means that the stratification was influenced by the wake and that waters above and below the thermocline were mixed with each other. However, three hours later the water has re-stratified and the mixed water has spread out laterally. We do not claim that there was a long-lasting effect on the stratification. However, during the longevity of the wake the stratification was most likely affected. Hence, in a scenario with very frequent ship passages, there will be less time for the re-stratification to occur, and a more long-lasting effect on the stratification could be possible.

To address this comment, we will clarify the aim of the paper as being mostly descriptive. However, we suggest keeping the current sentence, based on the arguments provided above.

Line 574-581: *As mentioned above, please try to find satellite imagery that covers the in-situ measurement area.*

As mentioned in a previous answer, satellite imagery covering the in-situ measurement area and period has been retrieved, but it was covered by clouds and impossible to use. A cloud free sky is needed for the satellite images to be usable, and the *in-situ* measurement area is too rainy to have a sufficient amount of cloud free images for the satellite study. Moreover, the Gothenburg area does not have as many ship passages as the Bornholm area, which is essential as you need to be sure to have ship passages at the time of the satellite passage. See also the previous answer regarding the choice of study area for the satellite study.

To address this comment, we suggest adding a sentence in the manuscript explaining the lack of cloud free satellite images from the *in-situ* study area and period, and the motivation for choosing the two different sites.

Line 587: *Note that winds are also important.*

We agree that winds are important, both as they affect waves and currents. As we have measurements of the water speed and waves, we consider the wind effect on currents and waves to be captured by those measurements. However, we acknowledge that the wind should still be mentioned.

To address this comment, we suggest adding wind to the sentence in line 587 and stating that as we have measured the water speed and waves, we consider the wind effect to be captured by those measurements.

Line 618: *What parameters?*

To address this comment, we will name the parameters that have been discussed in the paper in relation to the ship wake depth, to make it clear which parameters we mean.