Answers to RC1

***General comments**. The paper is mostly descriptive and practically no physical analysis of the observations is performed. It looks mostly like a report on some routine observations, like "a pile of data", and only methodological aspects of the work are discribed, although not clearly enough (see, some specific comments below). One cannot find in the text any new physical effects. The paper in its present form does not look interesting and informative from a scientific point of view. The aim/motivation of the paper is not clear.*

Regarding the general comment: "*The paper is mostly descriptive and practically no physical analysis of the observations is performed."* As indicated by the title, we acknowledge that the aim of the paper is to describe the phenomenon of turbulent wakes, and thus being "*mostly descriptive*". However, we humbly disagree that the paper is "*mostly like a report on some routine observations"* and that *"practically no physical analysis of the observations is performed"*. Even though the aim of the paper is to describe the extent of wake influence, we have made analysis of the turbulence in the wakes (dissipation rate of turbulent kinetic energy), which we have relate to natural turbulence. Furthermore, we have presented an example of what the described spatiotemporal extent of the wake would implicate in terms of temporal and spatial wake-impact/influence in a highly frequented ship lane. 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. The work of measuring large quantities of turbulent wakes in ship lanes, is far from routine, and not many observations have so far been published. Previously, studies on ship wakes used single (or a few passages), often of research or navy vessels, which does not give a good representation of the ships passing in a heavily frequented ship lane. We also measured and analysed the effect of currents on the wakes and wake detection. However, as mentioned in line 591–593, we chose not to show that data, as there was no clear effect of current speed or direction when it came to wake detection and wake depth/longevity. This analysis/data could of course be included in the manuscript or supplementary info, if whished for (Also see the answers to RC2 regarding the impact of wind). In addition, we would like to highlight the interdisciplinary nature of this work. The process of identifying and linking the wakes with the ship inducing the wake is time-consuming, but necessary to relate the wakes to the physical properties of the vessels. However, we agree and acknowledge that the vessel-related analysis can be developed further, and we have suggested how to do so in detail in the answer to that specific comment below.

Regarding the general comment "*only methodological aspects of the work are discribed, although not clearly enough (see, some specific comments below)"*, the specific comments are addressed individually below. Furthermore, we agree and acknowledge that there is a focus on describing the methodology of the work. That is because there are currently no published descriptions of best practice or standard methodologies to study ship wakes and passages in heavily trafficked ship lanes during an extended period of time without interfering with the traffic itself. It is an activity with many technical and practical challenges, and therefore, the methodology has been explained in detail. Moreover, most previous studies of the turbulent ship wake, have been performed using echo sounders/multibeam mounted on the ship hull of a small ship, which have travelled across the ship wake in serpentine movements behind the ship, measuring the wake from above. Here we propose a method based on upward facing instruments placed on the sea floor under the ship lane. We therefore consider it important to describe and discuss the methodology in detail, and we propose to add additional figures to illustrate the experimental setup, to clarify the questions asked (see detailed answers below).

Regarding the general comment *"One cannot find in the text any new physical effects"* and *"The paper in its present form does not look interesting and informative from a scientific point of view"*, we respectfully disagree. To our knowledge, there is no published dataset showing this consistent pattern of turbulent and temporal wakes, and no studies including more than a handful of different ships. The observed maximum wake depth presented in this study, exceed previously reported wake depths, which sheds new light on a novel perspective of the environmental impact from shipping. Moreover, the longevity and persistence of the thermal wakes shown in the satellite data highlights the importance of considering the impact of ship wakes in highly trafficked areas (with up 55 000 passages per year). This effect is important to raise awareness of, especially within the FerryBox community, as the temperature measurements made within ship lanes can be biased if they are made in the wake of another ship. The longevity of the temperature difference indicates that the ship wake water stays a separate entity (is not diluted/mixed) for a substantial period of time (+ 1 hour). Even though only temperature has been measured in this study, the thermal signal can be considered as proxy for the ship wake water, and potential changes in other chemical/physical parameters such as salinity, nutrient concentration etc. should also be sustained in the ship wake water as long as it is not mixed with the surrounding water mass.

Regarding the general comment: *"The aim/motivation of the paper is not clear".* Firstly, we suggest changing the title to: "*In situ* observations of turbulent ship wakes and their spatiotemporal extent", to clarify that the aim is to describe the characteristics of the turbulent ship wake. We will also rephrase the last paragraph (lines 105–115) in the introduction as below, to further motivate and describe the aim of the paper:

"The aim of this study is to obtain an overview of the magnitude of the spatiotemporal influence of ship-induced vertical mixing. Understanding the scales at which the wakes occur is the first step in estimating the environmental implications of ship-induced vertical mixing. Here, a combination of methods has been used to describe the depth, width, length, intensity and longevity of the turbulent wake for a large set of ship passages (~240). As the study has been conducted *in situ* and *ex-situ*, on different temporal and spatial scales, and includes ships of different types and varying size, it constitutes a solid base for a first estimate of the order of magnitude of the spatiotemporal extent of ship-induced vertical mixing. A better understanding of the spatial and temporal extent of the turbulent wake makes it possible to identify in which areas ship-induced vertical mixing could have an impact on local biogeochemical cycles. Moreover, it provides the means to estimate how large an area is, where an effect on gas exchange could be expected. In addition, it will provide valuable information for monitoring and studies of the dispersion of pollutants from ships, especially for the FerryBox community, where continuous s measurements are being made by ships on route in major ship lanes. In short, with knowledge about the spatiotemporal scales of ship-induced vertical mixing, comes the ability to identify when and where ship-induced mixing needs to be considered. This in turn would be a first step in filling the knowledge gap regarding the environmental impact of ship-induced vertical mixing."

Specific comments RC1

1. An error in formula (1)

Suggested change: from

$D_{11}(r, \Delta r) = \overline{\left(u_r'(r + \Delta r) - u_r'(r + \Delta r)\right)^2}$, to $D_{11}(r, \Delta r) = \overline{\left(u_r'(r) - u_r'(r + \Delta r)\right)^2}$.

2. A scheme of the ADCP deployment and recording of ship wakes has to be presented to understand how the ship wakes are recorded by the ADCP. For instance, the bubble wake manifestations similar to one in Fig.2 appear when the ADCP is towed across the ship wake, or if the wake is moving in the cross wake direction due to currents passing by the ADCP beams. How thus the record of a ship wake *in Fig.2 could be obtained for a stationary looking upward ADCP? Was that due to a current moving a wake through a zone illuminated by ADCP?*

We appreciate the suggestion of adding as scheme to describe the instrument deployment and recording. We suggest including Figure 1 (below) in the manuscript, at the material and methods section, together with a description. Moreover, we suggest adding an additional sketch in Figure 2 in the manuscript (as shown in Figure 2 below), to further illustrate what the ADCP is recording. In addition, we have also made some complimentary illustrations that could be added to the manuscript or a supplementary information section, if requested (see Figure 3, Figure 4, and Figure 6).

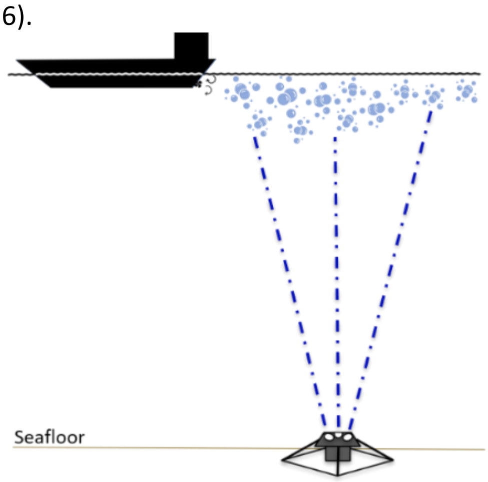

Figure 1. Scheme of instrument deployment, showing the ADCP, placed upward facing on the seafloor, recording the turbulent wake during a ship passage.

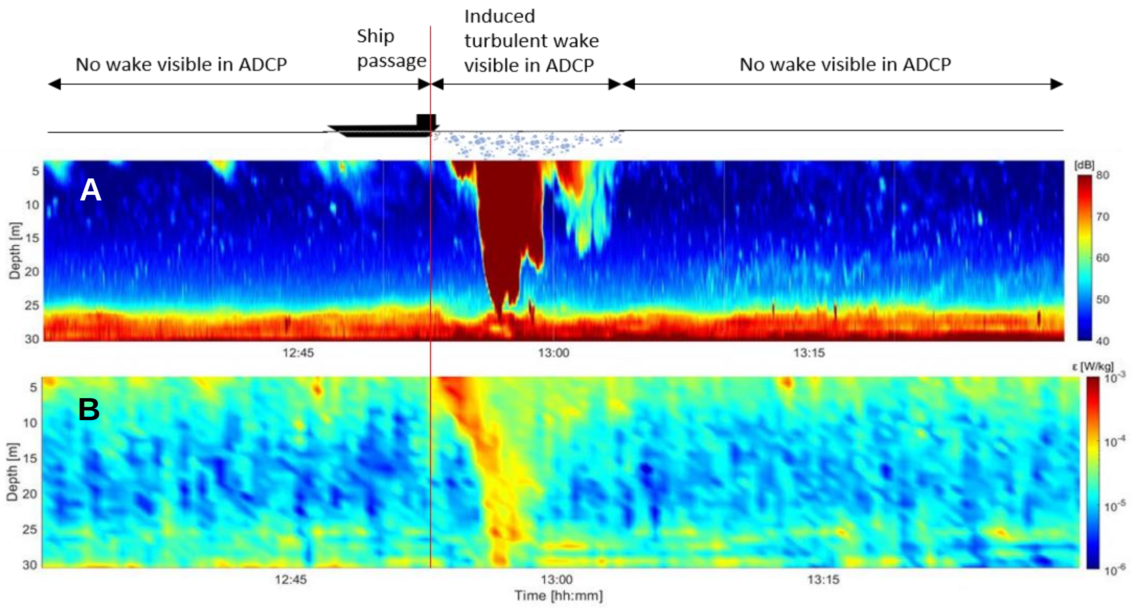

Figure 2. Example of the bubble wake signal in the echo amplitude dataset (a) and the calculated dissipation rate of turbulent kinetic energy, ε, (b) from the ADCP measurements. The high intensity red area represents the wake region. The increase of ε down to the bottom is evidence of increased turbulence and that there is vertical mixing down to 30 m depth in this case. The wake was induced by a RoRo-cargo ship (width 27 m, length 230 m, draught 7.7 m), which passed the instrument at a distance of 34 m and a speed of 19 knots. The ship and bubble wake above the panels indicate the point of ship passage (red line) and the induced wake measured by the ADCP. Areas where no wake is visible in the ADCP measurements, are also indicated.

The ADCP measures how the water column above the instrument changes over time. This is similar to measuring along the wake with a towed ADCP, but instead of moving the ADCP further away from the ship, the ship is moving away from the ADCP, thus the ADCP measures the "aging" of the wake in one point. As illustrated in Figure 3, the different times in the ADCP timeseries, corresponds to different distances behind the ship. Apart from defining what the ADCP measures in relation to time/distance to the ship, which cross section part of the wake that is measured is also of interest. Figure 4, Figure 6, and Figure 5 illustrate which part of the wake the ADCP is measuring, regarding to the wake cross section.

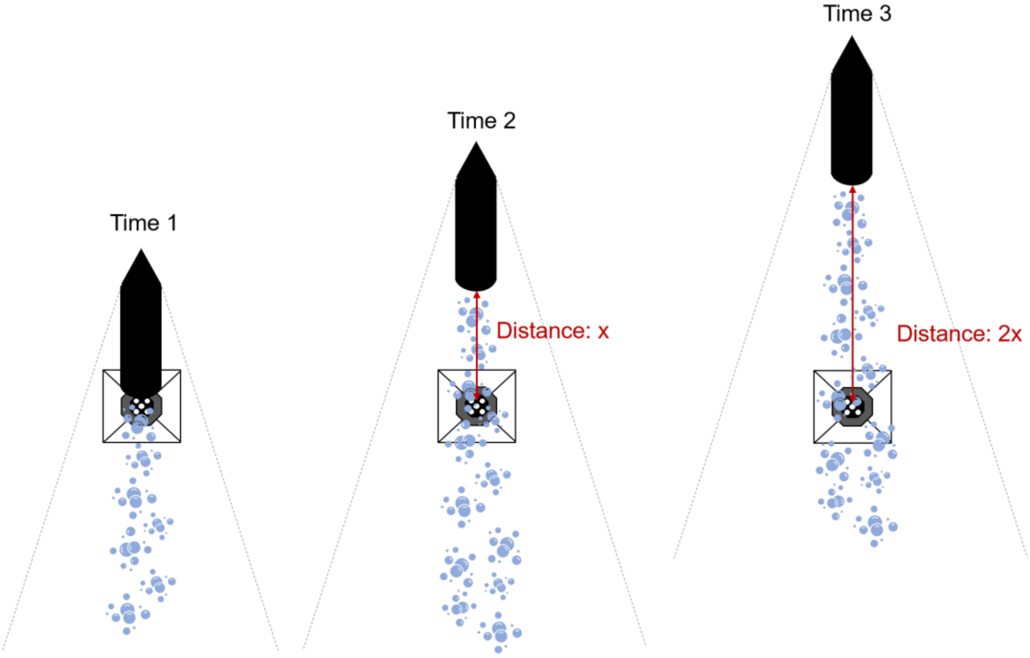

Figure 3. The ADCP measures in the same point over time, which corresponds to measuring the wake at different distances behind the ship. At time 1, the ship is just above the instrument, and the wake will correspond to the start of the wake. At time 2, the ship has moved distance x, which means that what the ADCP is measuring corresponds to measuring the wake at distance x behind the ship. At time 3 the distance is 2x, thus the ADCP measures the part of the wake corresponding to the distance at 2x behind the ship. The distance in length can be estimated if the speed of the vessel is known.

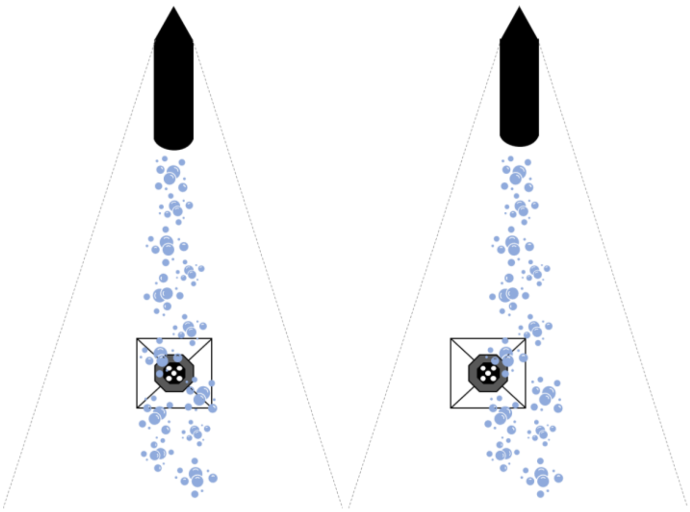

Figure 4. Illustration of which part of the cross-section of the wake the ADCP measures. The left example shows a scenario where the ship passes straight over the ADCP, thus measuring the aging of the middle of the wake. In the right example, the ship is passing to the right of the instrument, thus measuring the aging/development over time of the right edge/side of the turbulent wake.

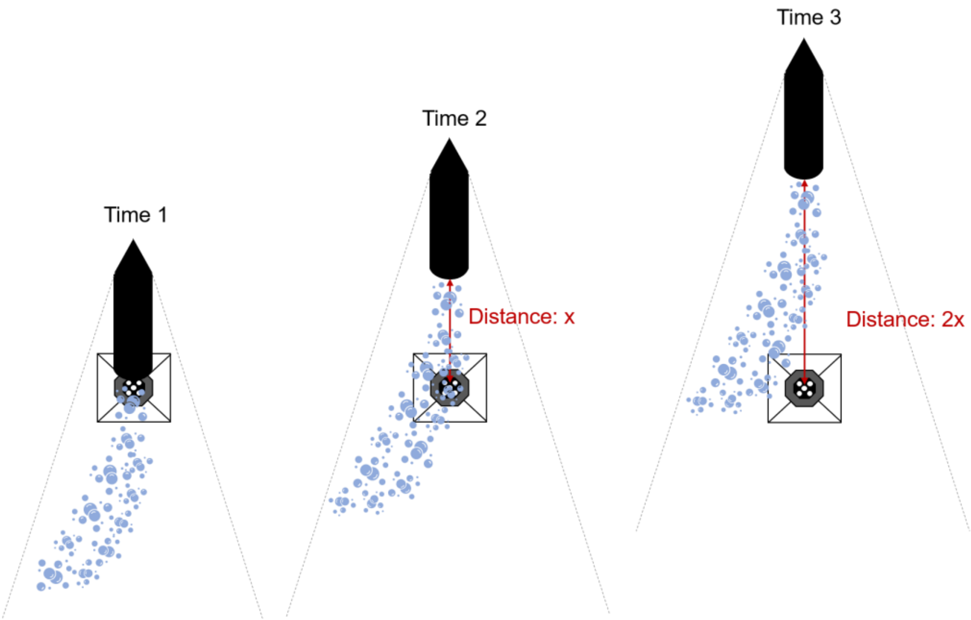

Figure 5. Illustration of how currents affect the measurement of the wake. If the current makes the wake drift away from the instrument, the ADCP will not measure the same part of the wake cross-section.

The illustrations in Figure 4 and Figure 6, assumes that there are no currents making the wake drift and Figure 5 illustrates what the ADCP measures in the presence of currents. In Figure 5, the water column above the ADCP loses the signal of the wake before it has truly disappeared, with regards to the distance behind the ship, which would result in a shorter wake compared to the actual wake. Moreover, the intensity and depth of the wake might vary in time due to the drifting, as different parts of the wake cross-section are measured over time. This would create a misleading image of how wake depth and intensity develop over time/with distance behind the ship.

3. Why the wakes appeared in the ADCP records for ships passed by at some distances from the ADCP? Because of the wake turbulent diffusion? If so, why not to analyze, e.g. the characteristic times of the turbulent diffusion, the diffusion spatial/temporal decay, etc.?

We consider two main reasons for the wakes appearing in the ADCP records for ships passing at some distance from the wake. Firstly, currents can move the wake towards the instrument. However, when looking at the impact of currents in our data, we could not see that that current speed and/or direction was affecting the existence of a wake in our data. Moreover, during most of the measurement period the current speed at the instrument position was very low. These two circumstances indicate that wake drift due to currents is probably not the main reason that wakes are detected from ships passing at long distances from the instrument.

The second possible reason, as suggested, is that turbulent diffusion widens the wake. As shown in the satellite data, the median thermal wake width was 157 m. Even though the thermal wake and the turbulent wake are not exactly the same, it still indicates that a ship passing at a distance of up to 150–200 m away from the instrument could induce a wake, where the edge of the wake eventually reaches the instrument. In addition, the wake will be widened by buoyancy effects if the water is stratified. We have indications from recent measurements that the turbulent wake can diffuse/spreads sideways along the pycnocline and is also to some extent “retained” at that depth.

There is also a reason why we have chosen not to analyse the characteristic times of the turbulent diffusion. As the ADCP only measure in one point, it is not clear if the entire length of the wake is captured or which part of the wake is being measured (see discussions regarding Figure 4 and Figure

5). Since it is not sure that the entire wake from start to end is measured, making calculations on diffusion rate based on it would not be fully representative. We intend to perform these more detailed calculations with a different environmental setup in future studies and do not consider it part of the scope of this paper. However, for the aim of the current paper – estimating the temporals extent of the turbulent wake, we considered the large quantity of measurements sufficient to give an estimate of the overall/general temporal extent, without analysing the characteristic times of the turbulent diffusion.

4. Line 301. I cannot understand how this can happen : "…when two ships passed the instrument at the same time"

Large ships may require pilot assistance and/or tugboats to enter the harbour. In these cases, the ships pass right next to each other and it is impossible to separate the wakes form the different ships (Figure 6, left). Most of the double passages in the dataset where these types of occasions. There were a few occasions where two ships passed the instrument at the same distance from the instrument, but on different sides (Figure 6, right). In these cases, it was not possible to tell which of the ships that induced the wake detected by the ADCP, as our analysis of the data showed now clear correlation between current direction and wake detectability. Hence wakes from these occasions were treated as a double passage, as the detected wake could come from either ship or be a combination of both passages.

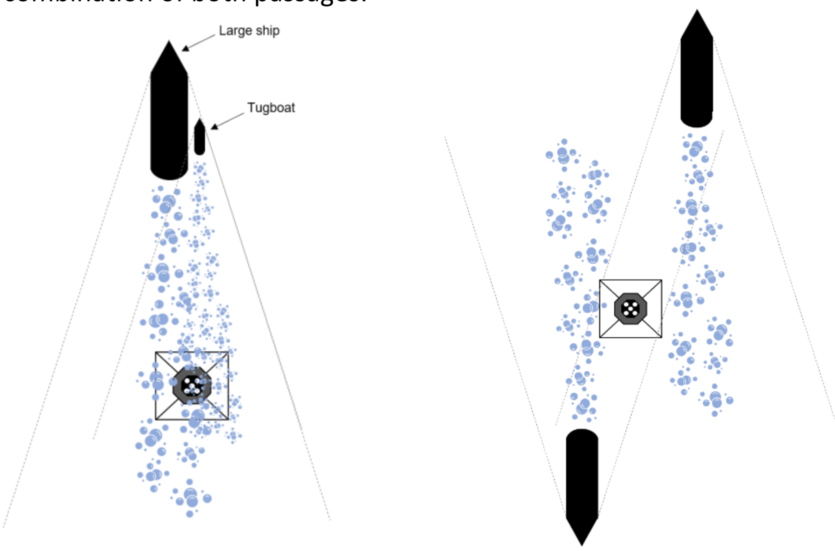

Figure 6. The left figure shows a large ship and a tugboat passing the instrument at the same time. The right figure shows two ships passing on opposite sides of the instrument at opposite directions. In both cases it is impossible to assign the wake to a single ship.

5. Categorization of the ships in the context of their turbulent wakes does not look physically justified. More reasonable would be to relate the wakes to the ship weight, draught, speed, possibly to the size/number of propellers.

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 7 and Figure 9 and/or Figure 8 and Figure 10 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 7 and Figure 8 shows the maximum wake depth for the bubble wake and dissipation rate of turbulent kinetic energy (ε) wake. The difference between the figures is that Figure 7 only shows the ships passing within 0-3 ship widths from the instrument (roughly corresponding to 75 m), whereas Figure 8 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.

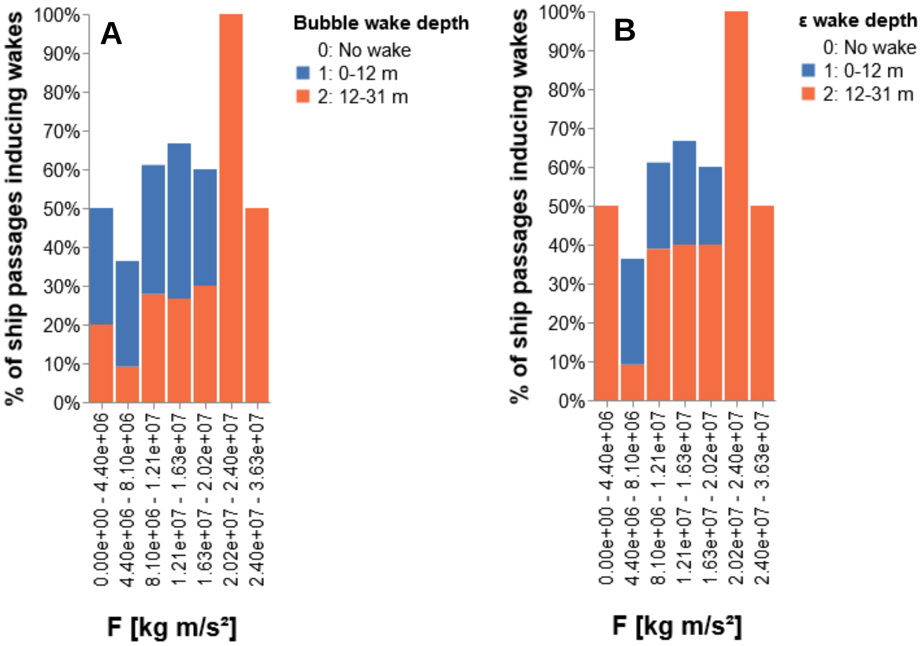

*Figure 7. Maximum wake depth for the bubble wake (a) and dissipation rate of turbulent kinetic energy (ε) wake (b), for the wakes induced by ships passing at 0-3 ship widths from the instrument. The x-axis shows the force (F) of the vessel in Newton, calculated as ρ*ship width*ship draught*ship speed^2. Wake depths within the range presented in previous studies are shown in blue and wakes deeper than previously reported are shown in orange.*

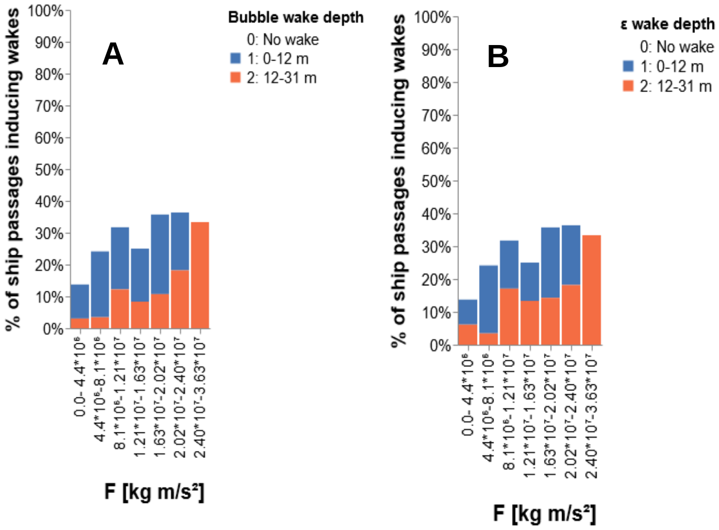

*Figure 8. Maximum wake depth for the bubble wake (a) and dissipation rate of turbulent kinetic energy (ε) wake (b), for all single passages. The x-axis shows the force (F) of the vessel in Newton, calculated as seawater density*ship width*ship draught*ship speed^2. Wake depths within the range presented in previous studies are shown in blue and wakes deeper than previously reported are shown in orange.*

Similarly, Figure 9 and Figure 10 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 11).

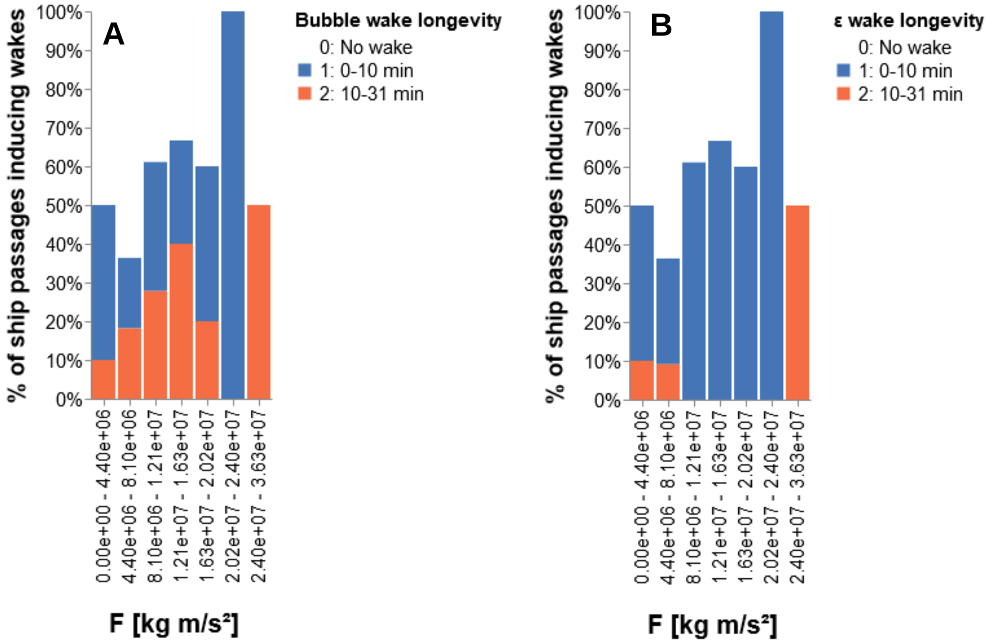

*Figure 9. Wake longevity in minutes for the bubble wake (a) and dissipation rate of turbulent kinetic energy (ε) wake (b), for the wakes induced by ships passing at 0-3 ship widths from the instrument. The x-axis shows the force (F) of the vessel in Newton, calculated as seawater density*ship width*ship draught*ship speed^2. Wake temporal longevities < 10 min are shown in blue and wake longevities 10–30 min are shown in orange.*

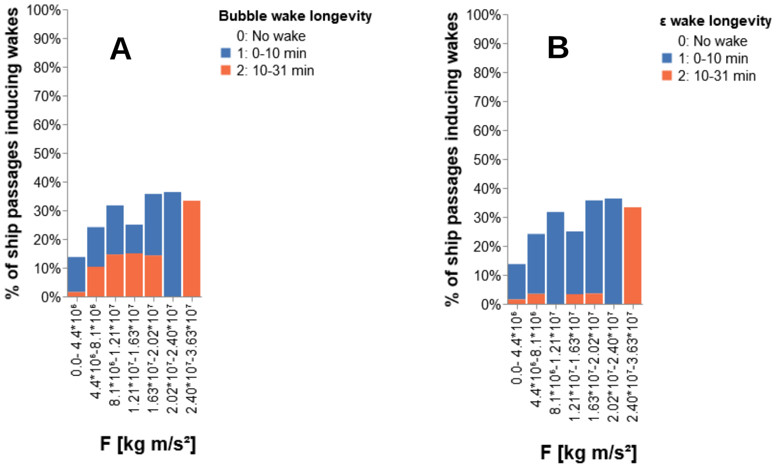

*Figure 10. Wake longevity in minutes for the bubble wake (a) and dissipation rate of turbulent kinetic energy (ε) wake (b), for all single passages. The x-axis shows the force (F) of the vessel in Newton, calculated as seawater density*ship width*ship draught*ship speed^2. Wake temporal longevities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

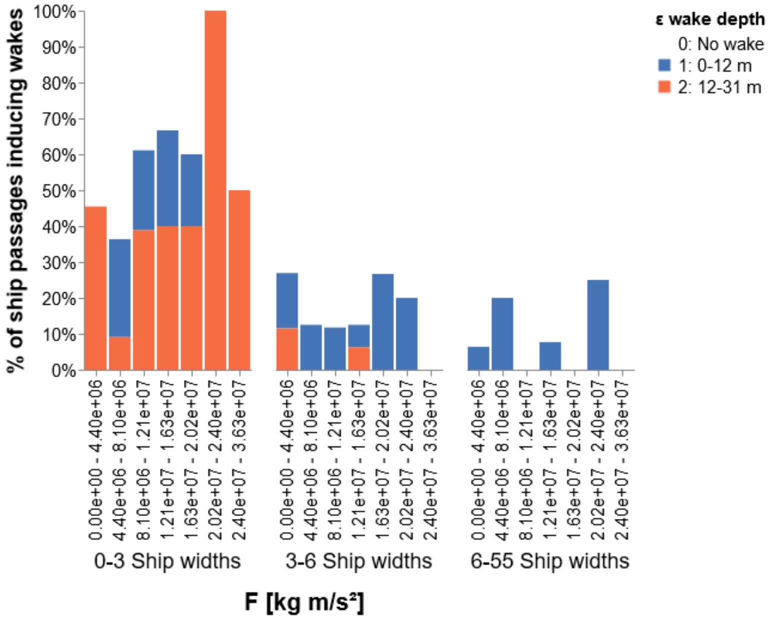

*Figure 11. Maximum wake depth for the dissipation rate of turbulent kinetic energy (ε) wake. The data is presented for three different categories of passing distances: 0-3, 3-6, and 6-55 ship widths from the instrument. For each distance category, the x-axis shows the force (F) of the vessel in Newton, 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 extent 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). This will 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.

We want to acknowledge that we agree that there are many factors which could affect the wake development, for example ship weight, dimension, speed, number and type of propellers, and hull shape. These are all features which are often shared within a ship type, as the type of ship is related to the purpose of the vessel, and thus the design. When choosing to use ship type as the category to divide the data into, we made the generalisation that the ship type categories entail ships of similar ship design (size, design speed, hull shape, shaft power etc.). We are aware that this is a generalisation, but it is not an arbitrary category; it is a category that on a general level combine/integrate the features listed in the beginning of this paragraph.

Before choosing the ship type category, we did look at how wake depth, longevity and intensity related to ship length, draught, and speed. However, none of these parameters alone explained the variation in wake depth and intensity to a very high degree, and there were no significant correlations between the wake depth or ship speed/length/draught. We therefore suggest to only present the data in relation to F, as it combines several of the most important parameters. However, if requested we could also include figures relating wake depth and longevity to ship length, draught, width, and speed in the supplementary information (Figure 12).

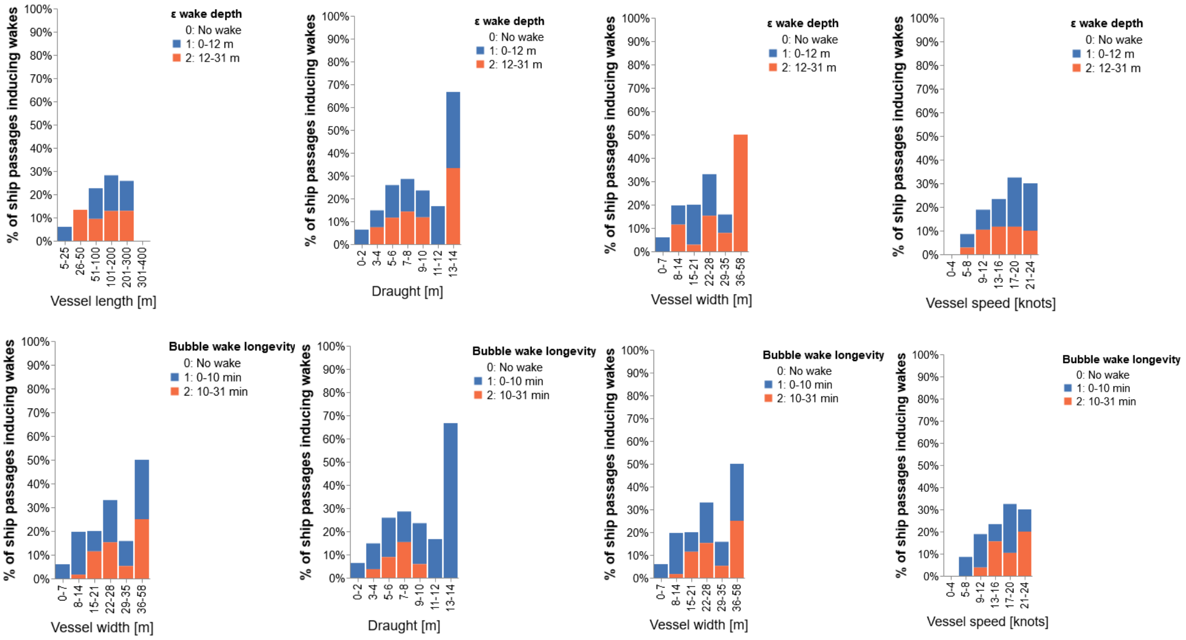

Figure 12. Example figures of how the vessel length, draught, width and speed relates to the ε maximum wake depth and bubble wake longevity, for all single passages in the dataset. Note that for all parameters but vessel speed, the categories with the highest values (rightmost bars) have very few passages (<10).

6. line 331 "As the fraction of detected induced wakes at similar distances differ between ship types, it is an indication that the ship type impacts the characteristic of the turbulent wake" . I disagree with the statement and I think that the difference is determined mostly by the ship weigh and ship speed.

This comment is addressed in detail in the answer to comment 5. As we now suggest replacing the figures which presents the data based on ship type, this sentence will be removed.

7. The paper is full of obvious, trivial statements, e.g. "in general the deepest wakes were caused by ships passing closer to the instrument, whereas ships passing at larger distances from the instrument (100–199 m) mainly caused shallower wakes : : :" (lines 369-370) "the maximum dissipation rates : : : in the core of the wake : : :.are : : :..much larger than what is usually observed in the core of, or below, the surface mixed layer" (lines 403-405), etc. etc.

We acknowledge and understand there are statements in the manuscript that can be perceived as trivial and obvious, depending on the researcher's specialisation. To balance the content to suit a diverse audience, from different highly specialised disciplines, is a general challenge in interdisciplinary research. Therefore, the second example in this comment was included for a reason. Our aim is to reach an interdisciplinary audience within ocean science, in line with the scope of this journal. This specific comment was included because the non-oceanographic co-authors of the paper explicitly asked for a comparison between our measured values and values that would occur naturally in the system. We believe that these types of statements fill an important function in making the content of the paper more accessible to an interdisciplinary audience. However, with the new suggested figures, much of the result section will be rewritten, and will make sure not to pay extra attention to this aspect.