Response to reviewer 1

12th February 2018

The authors thank the reviewer for their careful reading of our discussion paper, and for their helpful and constructive comments regarding its content and improvement. The text of the review is reproduced below in black type; our comments are in blue; and changes to the original discussion paper are presented in italics.

The paper presents some new glider observations from which (i) tidal currents have been estimated and (ii) the position of tidal mixing front as been established.

My main problem with the paper is that as it is currently written it is poorly focused although the title implies that the paper is methodological but at times it appears to be making claims as to deepening understanding re- shelf sea fronts, which I am not convinced it does.
We have clarified in the introduction that the paper consists of two parts – method and demonstration – and that we consider the method to be a key result of the work.

Page 3, line 34 *The method for calculating tidal velocities from DAC observations, outlined in section 2, is a key result of the work with potential applications beyond that presented in section 3.*

More so I believe as presented, the paper actually obscures at potentially novel scientific contribution.

Much of the analysis is based on the (now rather old) H/U3 theory for the positioning of shelf sea fronts and appears to push the theory further than it was ever intended. Firstly the theory was derived to explain the position of shelf sea fronts in terms of the balance between the stratifying influence of buoyancy input as surface heating. Yet the measurements presented were taken in the autumn, when the net buoyancy is negative and so contributes to mixing and not stratification. As such I would argue that the application of the model in the paper is not correct.
The h/u^3 theory, as the reviewer points out, was developed for fronts in summer and is a better predictor of frontal location at that time. We use it in this study primarily because, as RC3 acknowledges, we are using new methods (i.e. gliders) to revisit established ideas. While h/u^3 may not be as effective a predictor of frontal location in autumn as in winter, it is an important part of how we have come to understand fronts; we believe that it deserves to remain in the paper, even if it serves to confirm expectations that it is most suitable in summer.

There are also problems with the application of the model:

1) Use of the ancient air-sea heat flux parameterisations (eg. Ivanoff, 1977) – there are much more up to date parameterisations available. This is particularly important as these types of simple models have always struggled to get convection (the consequence of the negative buoyancy flux) correct.

The model is indeed a classic and well-used model; more sophisticated models exist with different air-sea flux parameterisations. Our goal is not to develop the closest simulation of the observations, but rather to explore the processes. The very simple model offers the best opportunity to do this, and indeed it is surprising how well the simple classic model performs.

2) The spring-neap motion of the front in response to changing U3. Note that there is an important feedback here – between turbulence driving mixing and stratification which limits the impact of the turbulence and so limits the spring-neap excursion of the tidal mixing front (I believe Simpson and Bowers, 1984 talk about this).

The reviewer is right to highlight that stratification limits the impact of turbulence and therefore spring-neap frontal excursion. Additionally, Simpson and Bowers (1981) highlight that the spring-neap frontal excursion is a more readily observed feature during frontal development in spring and into early summer. We have expanded on this point in our discussion.

Page 9, line 19	*There does not appear to be adjustment of frontal location with the spring-neap cycle, although the effects of such adjustment would be much greater immediately after frontal development – i.e. in late spring and early summer (Simpson and Bowers, 1981). Furthermore, some of the additional mixing energy available at spring tides is expended reducing stored potential energy on the stratified side of the front rather than moving the front itself, limiting the extent of spring-neap frontal adjustment (Simpson and Bowers, 1981).*

3) The model does not include the stratifying influence of freshwater which I believe to be important here.

We agree that the influence of freshwater is important in the region. It helps to maintain the salinity gradient between relatively fresh water of primarily coastal origin and relatively saline water of primarily oceanic origin. The absence of the zonal salinity gradient in the model is, we propose, the cause of the divergence between the model and reality in the final weeks of the deployment. We now discuss this in the context of water masses in section 3.2. We do not include freshwater in the model in order to isolate when heating-stirring interactions are the dominant control on frontal location. Adding salinity into the model would not allow us to do this.

Page 11, line 17	*The heating-stirring model cannot reproduce these water masses: they are not formed locally by heating-stirring interactions and their distribution in the northern North Sea is controlled by advection. The temperature distribution created by these water masses is such that a horizontal temperature gradient is maintained. In particular, the bottom front, which is the most dynamically significant feature of the frontal system (Hill et al., 2008; Sheehan et al., 2017) is maintained by the presence of the Atlantic-*

influenced CAW.

In particular it this later point which could form the basis of an interesting story, if the paper goes down the science route. The fact that after the disappearance of the thermal stratification there is still a lateral salinity gradient points to the development of seasonal stratification influencing shelf sea residual circulation even after the disappearance of seasonal stratification. Although not totally up to date with the literature, this is not a topic which I have seen discussed in the literature and so would be well worth pursuing.
We agree that the existence of the lateral salinity gradient is noteworthy. We have expanded the discussion of this in the paper.

Page 12, line 11 *The results of a one-dimensional heating-stirring model, and comparison of these results with glider hydrographic observations, demonstrated that salinity gradients and the distribution of water masses are important controls on frontal location in the region, in addition to surface heating and primarily tidal mixing. A water mass distribution exists which gives rise to a frontal boundary in temperature and salinity. In the absence of significant surface heating, this is the primary source of a frontal boundary and therefore the primary control on frontal location. In summer, heating-stirring interactions modify the water masses, enhancing the background temperature gradient such that heating-stirring interactions become the primary control on frontal location. This situation persists until the autumn: the observations presented in this study capture the period during which, in 2013, the front transitions from being primarily a tidal mixing front to being primarily a front between different water masses.*

Page 12, line 21 *Water mass distribution and attendant spatial gradients of thermal and haline buoyancy are likely to be important in shelf sea where significant incursions of oceanic water are found, such as the northwestern North Sea, the South China Sea (Shaw, 1991; Su, 2004}, along the eastern coast of the United States (Blanton et al., 1981) and around Antarctica (Moffat et al., 2009). Mixing fronts in such regions may persist during periods when local heating-stirring interactions would not promote frontal formation, and the controls on frontal location may change over an annual cycle.*

Response to reviewer 2

12th February 2018

The authors thank the reviewer for their careful reading of our discussion paper, and for their helpful and constructive comments regarding its content and improvement. The text of the review is reproduced below in black type; our comments are in blue; and changes to the original discussion paper are presented in italics.

General comments

This is a largely methodological paper that uses Seaglider derived depth averaged currents to calculate tidal velocities and amplitudes in a shelf sea environment. These tidal currents are compared to modelled tides and output from current meters before being used to define tidal mixing fronts. A combination of a simple model and hydrographic observations has been used to explain the positions of the fronts.

I think there is value in the methods presented within this work and that it has been done well. I do however have some concerns about how well some of the later analysis supports the conclusions and find that the general story gets lost because of this.

Introduction

Is the mixing front visible in satellite data? If so it would be interesting to add SST or a front map to figure 1 to highlight the co-location.

The mixing front is not really visible in satellite images taken during the deployment, and glider temperature observations record only a slight temperature decrease with distance offshore. In some years, particularly in the summer months, the front has a modest surface expression (Sheehan et al., 2017) but that does not appear to be the case at the time of our glider observations.

Method 2.1

I would be interested to see if the glider altimeter depths compare well to the GEBCO bathymetry. Given that the depth is so important to your analysis then glider depth might be more accurate.

We take bathymetry from the GEBCO database because we trust it more than bathymetry as determined by the glider, which could be inaccurate. The altimeter is a rudimentary instrument used primarily as a piloting tool; it does not continuously record the glider's height above the seafloor and it does not accurately detect the bottom on each dive. What is more, the response of the altimeter can differ with the composition of the sea floor (sand, sediment, rock etc.).

Page 5, line 8 *All bathymetry data used in this study were extracted from the GEBCO dataset (GEBCO_08 grid, version 20100927, www.gebco.net; resolution 30 arc-seconds). While it is possible to estimate bathymetry from the glider's altimeter* *observations, we believe that bathymetry from a databank for a well-studied region such as the North Sea is likely more accurate.*

How have you combined the M_2 and S_2 tides? You often use M2-S2 as a concatenation and this suggests that you subtracted S2 from M2. You also need to be consistent in you notation for this combination throughout the text.

The zonal components of the M_2 and S_2 tides have been added together, as have the meridional components of the M_2 and S_2 tides. The abbreviation has been changed to M_2+S_2 throughout in order to make this clear and the abbreviation has been defined.

Page 5, line 25 *Combined M_2 and S_2 (hereafter denoted M_2+S_2) zonal and meridional velocities were then calculated at the time of each glider dive.*

You have interpolated the velocities to give "along-track" glider velocities and then reference Figure 4 which shows "meridional" and "zonal" velocities. Have you assumed that the along track direction is zonal? This needs to be made clear as the glider tracks are rarely completely zonal.

The along-track velocity time series comprises estimates of tidal velocity at the time and location of each glider dive: it is the location of the data points in time and space that we describe as along-track (i.e. following the glider's track), not the velocities themselves. The text has been amended to make this clearer.

Page 5, line 26 *Tidal velocity was linearly interpolated zonally onto that dive's location to construct a time series of tidal velocity along the glider's overground track – that is, a time series of tidal velocities with data points at the time and location of each dive. These are hereafter referred to as along-track velocities.*

How were estimates extracted from the TPXO model? I assume the TPXO model has some interpolation or smoothing and as such the points within it aren't entirely independent. In contrast the glider DACs are independent from each other. Have you accounted for this difference between models and observations?

The TPXO European shelf model has a 1/30° grid of amplitude and phase estimates for 11 tidal constituents. Velocities are extracted from the TPXO model using the Earth and Space Research Tidal Model Driver software for Matlab (esr.org/research/polar-tide-models/tmd-software), which interpolates between TPXO grid points to make predictions. The reviewer is correct that the DACs are independent. We do not apply smoothing or filtering prior to the harmonic analysis.

Page 6, line 18 *To compare the results of our method with an established alternative, estimates of M_2 and S_2 amplitude, phase and velocity, were extracted from the TPXO inverse model European shelf solution (0.1° resolution; Egbert et al., 1994; Egbert and Erofeeva, 2002; Egbert et al., 2010) using the Tidal Model Driver software for Matlab (available at esr.org/research/polar-tide-models/tmd-software).*

Method 2.2

You explain the statistics and process of binning the data after you have introduced the binned data. However I think you do need to maintain the discussion of the accuracy at the end of this section and so some restructuring is required.

The final paragraph of section 2.2 has been moved into section 2.1 so that discussion of the accuracy of the ellipses and the number of dives needed in each bin comes directly after the method has been explained. All discussion of the method and related considerations (number of dives, number of bins etc.) is now in the same section, and section 2.2 is just a discussion of the ellipses as presented in Figure 3.

Frontal location

The structure of this section is very abrupt, with little initial introduction. Paragraph 2 is difficult to follow and again would benefit from restructuring. The information is all there but the story gets lost.

Section 3 has been given a longer introduction that we hope better introduces the work on frontal location. Paragraph two of this section in the discussion paper has been restructured and amended to improve the writing.

Page 8, line 9	*We apply the glider-derived tide presented in the previous section to study the location of a front in the north western North Sea. Specifically, we investigate the extent to which the location of the front may be explained by heating-stirring interactions, a principal component of which is tidal speed. Furthermore, this analysis serves as an illustration of a potential application of the method (section 2).*

Why have you focussed a large part of this section on work by Simpson and Sharples, which you say is not appropriate for this region? It would be nice to see more discussion of Hughes which appears to be more suitable to this work.

The theory of frontal location stems in no small part from the work of Simpson and Sharples (and co-authors), hence the prominence of their work in our discussion. We believe that this work is of great relevance to our study, not least because we are seeking to understand similar phenomena. Hughes (2014) refines the conclusions of Simpson, Sharples and co-authors – principally by providing a value of h/u^3 applicable to our study region and attributing this updated value to local surface heat fluxes – but does not change the fundamental concepts on which we rely. We therefore believe that the papers of Simpson, Sharples and co-authors, as updated by Hughes (2014), are important references for our study and receive appropriate attention. As suggested by the reviewer, more discussion of Hughes (2014) has been added.

Page 9, line 6	*Hughes (2014) using a heat flux appropriate to the northwestern North Sea, concluded from a modelling study that the critical value for frontal location in the region should be 3.4; the applicability of this value was confirmed by examination of 28 years (1982 – 2008 inclusive) of satellite observations of sea-surface temperature (Hughes, 2014). The higher critical value is attributed to the reduced heat flux and enhanced wind mixing at the latitudes of the northwestern North Sea compared with the latitudes of the Celtic Sea (Hughes, 2014) the site of much previous work*

on the h/u^3 criterion (e.g. Simpson and Hunter, 1974).

In the final paragraph you say that there "does not appear to be adjustment" and then explain the effects of the adjustment, is there adjustment?

"Are" (discussion paper: page seven, line 11) has been changed to "would be" to make clear that we are presenting a potential reason for the lack of adjustment, rather than seeming to imply that there is adjustment.

Page 9, line 19 *There does not appear to be adjustment of frontal location with the spring-neap cycle, although the effects of such adjustment would be much greater immediately after frontal development.*

Comparison with model output

Again the story gets a little lost due to the structure here. I think a short section linking the observation of the front to this analysis of it. Say upfront what it is you're trying to get out of the comparisons.

Why was this model chosen?

We address the above two comments together. The opening of section 3.1 has been expanded to both better motivate our use of the model and to explain why we have chosen to use the Simpson and Bowers (1984) heating-stirring model

Page 9, line 30 *We compare the observations of frontal location with the output of a numerical model of heating-stirring processes to identify which factors control frontal location during the period of the glider deployment. We use the open-source, one-dimensional heating-stirring model of Simpson and Bowers (1984, see also Elliott and Clarke, 1991, and Simpson and Sharples, 2012). The model is straight-forward to run; it's may be readily adapted to suit the study region and to work with the glider-derived tide described in section 2; and it includes only the physical heating-stirring processes used to describe frontal location by Simpson and Hunter (1974) and Simpson and Bowers (1984), and described in section 1. Consequently, the model allows us to investigate the extent to which heating-stirring interactions influence the location of the observed front (Fig. 5).*

Why has the 1st of November been selected as a representative date?

The explanation given in the discussion paper about how the velocities used in the heating-stirring model were chosen was not clear. This has been improved. 1st November was used because it falls midway between neap and spring tides.

Page 10, line 18 *We take as the tidal speed the meridional M_2+S_2 velocity amplitude midway between spring and neap tides (1st November), and use the glider-derived tide to capture the offshore decay in tidal amplitude.*

Comparison with observations

When you discuss the salinity gradient I think it would be interesting to show this, for example by a plot of the salinity gradient along a representative isobath, or something similar. This section is very interesting and a good argument for why the model doesn't hold up in October but I'm not sure it is sufficient to support your conclusion of a hybrid front. This is a qualitative assessment of the glider, which I would expect to be more thorough in order to be a full discussion item and to have such an influence on your discussion.

Based on analysis of the glider data carried out since the discussion paper was submitted, and in response to the reviewer's perceptive comment, we have re-written section 3.2 to shift the focus away from salinity – which is a little over-simplistic – and towards the hybrid front being formed between multiple water masses. The introduction has been modified accordingly. This does not change the conclusions of the study, but it does better reflect a situation in which the salinity distribution is more nuanced than our discussion paper implied.

Page 11, line 22	*The glider observations presented in Figs. 5 and 7 demonstrate that a front can exist in the northwestern North Sea independently of heating-stirring interactions. Such a front is clearly not simply a tidal mixing front. However, during the first part of the deployment, the observed frontal location compares well to frontal location as predicted from consideration of only heating-stirring interaction. We propose that the observed front is a hybrid between a tidal mixing front and a front which forms due to horizontal gradients between adjacent water masses in a region of complex water mass interaction.*

Do you have data to show that October (your early glider transects) is representative of summer as this section implies?

We emphasise that the observations presented in Figure 5a cover the period when the front makes the transition from its proposed summer state to its proposed winter state. We compare summertime frontal position in the model (when forced with a multi-decade average annual cycle) with summertime frontal position in the multi-decade average observations of Sheehan et al. (2017).

Page 11, line 28	*In summer, we propose that local heating-stirring interactions modify the water masses to the extent that the front is moved to a position as predicted by consideration of heating-stirring interactions alone. The present study does not include observations of the front at this time, but when forced with an annual cycle of multi-decadal mean meteorological values, the heating-stirring model places a tidal mixing front at approximately 1.5° W in summer; the front is found at the same location in multi-decadal summertime averages of JONSIS section hydrography (Sheehan et al., 2017). The observations presented in this study (Fig. 5a) capture the period in the annual cycle when, in 2013, the front makes the transition from being a front controlled by heating-stirring interactions to being a*

front controlled by the distribution of water masses.

Figures

Figure 2a and 3 should be the same geographical area, the one highlighted in Figure 1.

The area shown in Figure 2a has been changed – as has that highlighted in Figure 1 – to match the area shown in Figure 3.

Why has the shaded area/zoomed in Figure 4 been selected? It appears to be when the fit is best, maybe a central point or even a period when the fit is worst would be more appropriate.

The zoomed area in Figure 4 had been selected at random. It has been changed to cover a period where the agreement between the two time series is not so good (12:00, 30th October – 12:00, 2nd November)

Technical corrections

You have used a mixture of Fig. and Figure throughout, be consistent.

"Figure #" has been changed to "Fig. #" throughout.

2.2 line 10: "Ellipses from both" – you have 3 data sources here not 2

3 line 19: "critical contour" – should it be "critical value"?

Page 9, line 9	*The higher critical value is attributed to the reduced heat flux and enhanced wind mixing*

3 line 32: When was the final occupation of the section?

Page 9, line 25	*It then widens considerably towards the end of the deployment, being spread between 1.4 and 0.8 °W at the time of the final occupation of the section (19th November – 1st December)*

3.1 line 38: glider has been spelt glided

Response to reviewer 3

12th February 2018

The authors thank David Bowers for his careful reading of our discussion paper, and for his helpful and constructive comments regarding its content and improvement. The text of the review is reproduced below in black type; our comments are in blue; and changes to the original discussion paper are presented in italics.

This paper is about using a glider to study the position and movement of a front at the north-west entrance to the North Sea. The front is a boundary between mixed and stratified water and seems to have a mixture of causes: tides are important in creating the mixed water; the stratification is produced by a combination of surface heating, freshwater input and currents from the Atlantic.

The authors will likely disagree with me, but it seems to me that gliders are a solution still looking for a meaty problem to get their fins into, at least in shelf sea oceanography. Fronts could be just what they are looking for. Fronts are not always straightforward to find and so moorings, if misplaced by a few kilometres, might miss them altogether. Ships, for reasons of cost, are limited and satellites can only see the surface. Programming a glider to make repeated transits of a front (with a generous allowance for frontal movement), as has been done in this work, can lead to useful new knowledge.

We agree with the point made by the reviewer and we have incorporated it into the text.

Page 3, line 14	*The front is bottom-intensified and has only a limited signature at the surface (Hughes, 2014; Sheehan et al., 2017). Consequently, the front may be more readily observed from a profiling glider than from satellite observations of, for instance, sea-surface temperature.*

It's some years since I've worried about these problems but the observations presented here, are among the best set of observations of the autumn retreat of a front that I have seen for a while. There are a few things I would invite the authors to comment on. One of the most important things which moves a front in a shelf sea is the tide itself. The front will be in a different place at low water slack, say, than high water slack. The difference can be a dozen kilometres or so. I don't think the authors have corrected their observations to allow for this. Is that right? If so, it's not a big issue: it will introduce noise into their observations rather than bias, but it would be interesting to know how easy it would be to do this with glider measurements.

We have not attempted to correct our observations of frontal location for tidal displacement. To estimate the uncertainty this adds to our observations, we calculate mean zonal tidal displacement: we integrate zonal velocity over half a tidal cycle. We take as the velocity amplitude the mean absolute zonal velocity amplitude over the deployment.

The correction could be performed from our data. It would first be necessary to estimate zonal M_2+S_2 displacement at the time and location of the observation; this would be a function of the phase of the spring-neap cycle and position on the section. Secondly, one would need to chose a phase of the M_2 tide as a baseline phase – perhaps 0 or π radians. By comparing the phase of the zonal M_2 tide at the time and location of the observation to the baseline phase, one could then calculate what proportion of the total zonal M_2+S_2 displacement to apply as a correction. We have decided not to apply this correction to our data. It would require detailed explanation and illustration that would likely distract from the message of the second part of our discussion paper.

Page 8, line 17 *Observations of frontal location are not corrected for zonal tidal advection of the front. Instead, we acknowledge a zonal uncertainty in frontal position of ± 2 km (0.04° longitude), that being the mean zonal tidal displacement during the deployment.*

The appropriateness of the h/u3 criterion for a front which may have other causes than heating and stirring has been commented on by another reviewer and I won't dwell on that. The results shown in figure 5a are impressive, I think. It's a very nice set of observations of the autumn retreat of the front compared to a simple theoretical prediction. One thing I don't understand about this figure is why there are several yellow spots on each crossing. Where there several fronts?

There are several yellow dots for many crossings of the front (as opposed to just one frontal position being produced by the heating-stirring model) because the real world is a little noisier than the model. Specifically, the front frequently extends over a wider zonal distance that the distance between glider dives, which were only some 300 m apart; therefore the glider observes multiple locations at which the top-bottom temperature difference equals 0.5°C. This is one reason why, when calculating the rate of offshore frontal movement, we use a line of best fit instead of joining up the dots, as could be done with the model output. (The other reason is to calculate an average rate over the entire deployment.)

Page 8, line 16 *On a number of crossings of the front, the top-bottom temperature difference equals 0.5°C at a number of points (Fig. 5a). This is because the front often covers a zonal distance wider than that between glider dives.*

Of course, in the autumn, heating is no longer important: the tide and wind together are eating away at the buoyancy stored over the summer. The cooling of the surface in the autumn is helping and there may be an influence from the Atlantic. The authors might like to construct their own model with these processes in (not now, but for a future paper) and see if this fits the observations better?

This is as much a methods paper as anything and I have a couple of questions about that. First, the authors have used u from the glider and h from a data bank to test front position as measured by surface-to-bottom temperature difference, also measured by the glider. Why those choices of data sources, I wonder. Could everything be determined from the glider? Does it know how deep the water is that it is gliding through? Or would it be better to use current velocities from a model? We all do this – select data from wherever we think is best, but maybe in this case some justification of the choice would be good.

It is possible to estimate the depth of the water column from glider observations. The glider carries an altimeter with which it measures distance to the bottom. Adding this to the depth measured by the glider's pressure sensor at the time of the altimeter observation gives the depth of the sea floor. We take bathymetry from the GEBCO database because we trust it more than bathymetry as determined by the glider, which could be inaccurate. The altimeter is a rudimentary instrument used primarily as a piloting tool; it does not continuously record the glider's height above the seafloor and it does not accurately detect the bottom on each dive. What is more, the response of the altimeter can differ with the composition of the sea floor (sand, sediment, rock etc.).

We use tidal velocities from the glider rather than a model in order to demonstrate a potential application of our method and because the comparison of the glider- and TPXO-derived tides proves that the two data sources are of comparable accuracy.

Page 5, line 8 *All bathymetry data used in this study were extracted from the GEBCO dataset (GEBCO_08 grid, version 20100927, www.gebco.net; resolution 30 arc-seconds). While it is possible to estimate bathymetry from the glider's altimeter observations, we believe that bathymetry from a databank for a well-studied region such as the North Sea is likely more accurate.*

Finally, I'm a little surprised that the water velocity is so close to the glider velocity that the glider velocity can be used to give the depth-averaged current. Does the glider not move relative to the water to glide through it?

Similarity between the dive-average current and the glider's velocity should not influence the accuracy of a dive-average current observation. While underwater, the glider cannot communicate with a GPS satellite and so can estimate its position only by dead reckoning. On surfacing, the glider is able to compare its position as estimated by dead reckoning with its actual position as determined by GPS. The difference, along with the duration of the dive, is used to calculate the dive-average current. The accuracy of these observations is improved post-deployment by optimising a hydrodynamic model of the glider's flight path.

Page 5, line 12 *DAC observations are obtained incidentally during a glider's flight as the glider is advected by the flow over the duration of a dive-climb cycle. On surfacing, the glider compares its actual, GPS-determined position with its position as estimated by dead-reckoning, the difference being attributed to advection by the DAC. The accuracy of DAC observations was improved post-deployment by optimising the hydrodynamic model of the glider's flight (Frajka-Williams et al., 2011)*

I think this is an interesting paper using new methods to tackle an old problem. Thank you for letting me read it.

Response to reviewer 4

12th February 2018

The authors thank Emma Heslop for her careful reading of our discussion paper, and for her helpful and constructive comments regarding its content and improvement. The text of the review is reproduced below in black type; our comments are in blue; and changes to the original discussion paper are presented in italics.

This paper is assessing the methods and application of using a glider data from a single transect occupation, spanning several months, to determine tidal velocities, frontal position and the controls on this position. The paper was divided into 2 parts; assessment of the method and then use of the data. The method appears more leading edge than the application of the data to the problem.

This is a novel use of glider data to determine tidal velocities and the location of a front for analysis of drivers; this is an application worth highlighting for the reasons given and demonstrates that gliders are able to cost effectively provide data on ocean variability at sub seasonal scales. This is important to advancing our understanding of the interplay, at different scales, of drivers of ocean variability and improving model representation. Overall I think this work has value in highlighting this method and application for gliders. I have provided a couple of comments and a couple of minor edit notes.

1. The glider accuracy of the glider estimated DAV is dependent on the gliders internal compass and flight model used for the calculation, many authors including those cited in the paper recommend a procedure for correcting or calibrating the glider compass (Merckelbach, Smeed & Griffiths, 2010, Todd et al. 2011). For example 'swinging' the glider in a cradle/table, which produces a compass correction curve, similar to those traditionally produced for ship compasses (e.g. used with Spray/Slocum), or in situ spiral calibration flight (e.g. used with Seaglider). The article mentions visually inspecting the data, however it is worth expanding on this point. Although the comparison of the results is compelling and suggests the data is not overly affected by compass error, it is presumably one of the sources of error.

No compass calibration dive was recovered from the JONSIS line mission. In addition to the original visual inspection, we repeated the analysis using DACs from only east- and westbound occupations. Tidal ellipses from each sample show no systematic offset; we include the comparison plot below (Figure 1).

Page 5, line 16 *DAC observations were visually inspected to ensure that there were no systematic errors due to the glider's compass calibration, and the method described in this section was repeated using DAC observations from only east- and westbound occupations. No systematic difference between results obtained from the two samples was found, indicating that the observations are not affected by compass error.*

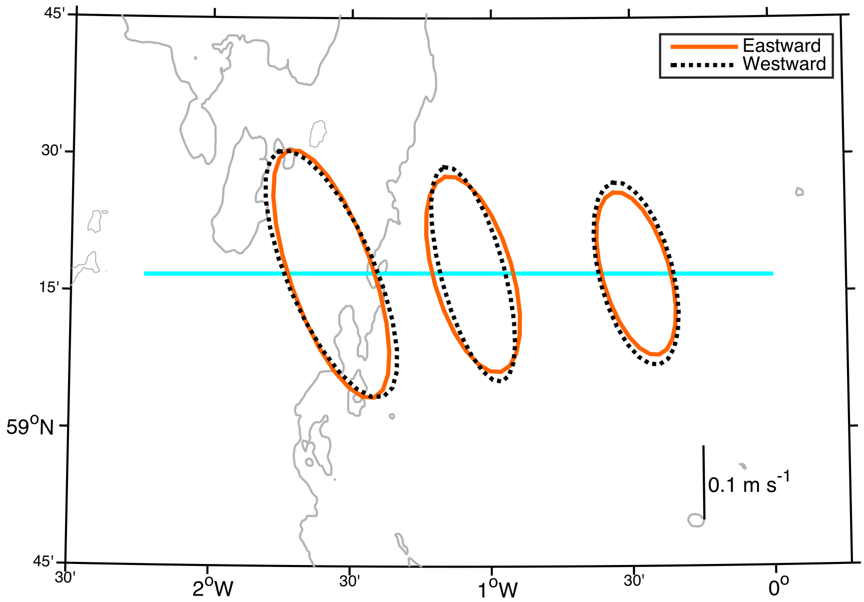

Figure 1 Tidal ellipses from only east- (orange, solid) and westbound (black, dashed) occupations

2. A significant part of the paper is about the novel method and potential benefits to other areas. Could it be worth summarising recommendations for future projects?

We thank the reviewer for an excellent suggestion, and we have added in recommendations for future projects.

Page 8, line 1	*1. Obtain repeat occupations of the same transect.* *2. Set the transect length so as to avoid aliasing the spring-neap cycle – i.e. avoid individual occupations lasting around one or two weeks.* *3. Optimise the hydrodynamic model of the glider's flight (Frajka-Williams et al., 2011) to obtain accurate DAC observations.* *4. Do not attempt to resolve more constituents than may be accurately resolved given the length of each binned, discontinuous time series.*

3. I am not a tidal expert, however the model used seemed potentially old and so the utility/reason for selecting this model could be better explained. If it is to only to indicate when heating is dominant, is the variability that we see between glider and model in the earlier part of the study a result of mixed dominance/drivers in this period?

The reviewer is correct that we use this simple model to identify when heating-stirring interactions are the dominant control on frontal location. We have improved our justification of model choice in the revised manuscript.

Page 9, line 30	*We compare the observations of frontal location with the output of a numerical model of heating-stirring processes to identify which factors control frontal location during the period of the glider deployment. We use the open-source, one-dimensional heating-stirring model of Simpson and*

Bowers (1984) (see also Elliott and Clarke, 1991, and Simpson and Sharples, 2012). The model is straight-forward to run; it's may be readily adapted to better suit the study region and to work with the glider-derived tide described in section 2; and it includes only the physical heating-stirring processes used to describe frontal location by Simpson and Hunter (1974) and Simpson and Bowers (1984) and described in section 1. Consequently, the model allows us to investigate the extent to which heating-stirring interactions influence the location of the observed front (Fig. 5).

Minor edit notes

Comparison with model output: 4th paragraph, line 6.
"Tidal stirring becomes ever more dominant" – change every to ever
Comparison with model output: 4th paragraph, line 8.
"(main front ±1.59 km day-1 ±0.08 km day-1; excludes the secondary front…)" – some suggested re-wording, as it took a couple of minutes to work out what this meant.

Page 11, line 2 *(1.59 ± 0.08 km day^{-1}; rate excludes the secondary front that emerges on 15th November 2013 around 0.1° W*

Shelf sea tidal currents and mixing fronts determined from ocean glider observations

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Abstract. Tides and tidal mixing fronts are of fundamental importance to understanding shelf sea dynamics and ecosystems. Ocean gliders enable the observation of fronts and tide-dominated flows at high resolution. We use dive-average currents from a two-month (12th October – 2nd December 2013) glider deployment along a zonal hydrographic section in the ~~northern~~ northwestern North Sea to accurately determine M_2 and S_2 tidal velocities~~, which~~. The results of the glider-based method agree well with tidal velocities measured by current meters and ~~extracted from a~~ with velocities extracted from the TPXO tide model. The method enhances the utility of gliders as an ocean-observing platform, particularly in regions where tide models are known to be limited. We then use the glider-derived tidal velocities to investigate tidal controls on the location of a ~~tidal mixing front. During the deployment, the~~ front repeatedly observed by the glider. The front moves offshore at a rate of 0.51 km day^{-1}. During the first ~~period~~ part of the deployment (~~i.e.~~ from mid October until mid November), ~~the front's position is explained by the local balance between tidal mixing and~~ results of a one-dimensional model suggest that the balance between surface heat fluxes and tidal stirring is the primary control on frontal location: as heat is lost to the atmosphere, full-depth ~~tidal~~ mixing is able to occur in progressively deeper water. In the latter half of the deployment ~~, the output of a simple one-dimensional model suggests that the front should have decayed. By comparing this model output to hydrographic observations from the glider, we~~ (mid November to early December), a front controlled solely by heat fluxes and tidal stirring is not predicted to exist, yet a front persists in the observations. We analyse hydrographic observations collected by the glider to attribute the persistence of the front ~~beyond this period to the advection~~ to the boundary between different water masses, and in particular to the presence of cold, saline Atlantic-origin water ~~across~~ in the deeper portion of the section. ~~The glider captures the transition of the front from being one controlled by the balance between tidal mixing and surface heating,~~ We combine these results to propose that the front is a hybrid front, controlled in summer by the local balance between heat fluxes and mixing, and which in winter exists as the boundary between water masses advected to the northwestern North Sea from diverse source regions. The glider observations capture the period when the front makes the transition from its summer- to ~~being one controlled by advection of buoyancy. Fronts in shelf~~ winter-time state. Fronts in other shelf sea regions with oceanic influence may ~~be geographically fixed and persist during periods of little to no thermal stratification, with~~ exhibit similar behaviour, with controlling processes and locations changing over an annual cycle. These results have implications for the thermohaline circulation of shelf seas.

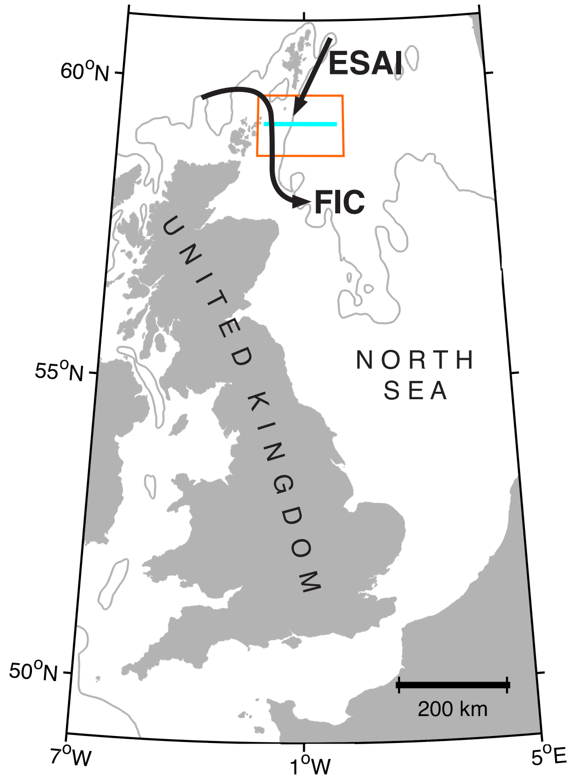

Figure 1. The location of the JONSIS ~~hydrographic~~ section (cyan line) in the northwestern North Sea. The approximate paths of the Fair Isle Current (FIC) and East Shetland Atlantic Inflow (ESAI) (Turrell et al., 1996) are shown. The area shown in Fig. 2a and Fig. 3 is enclosed in the orange box. The 100 m isobath is shown in grey.

1 Introduction

Tides are of fundamental importance ~~to~~ for understanding shelf sea dynamics and ecosystems. Not only are tidal currents frequently the dominant ~~circulation pattern~~ flows in these regions (Otto et al., 1990), ~~but~~ the turbulence, bottom-mixing and circulation patterns to which they give rise have a profound effect on the physics, biogeochemistry and ecology of shelf seas (Simpson and Hunter, 1974; Lenhart et al., 1995; Holt and Umlauf, 2008). In shallow regions with fast tidal currents, full-depth mixing is maintained throughout the year. In deeper regions, or where tidal currents are slower, tidal mixing cannot overcome buoyancy forcing in summer and the water column stratifies seasonally. The boundaries between mixed and stratified areas are sharp (∼20 km; Hill et al., 2008) and are known as tidal mixing fronts. ~~Such~~ These fronts separate water masses with markedly different physical and biogeochemical properties, and the density-driven jets to which they give rise are important transport pathways (Hill et al., 2008). Consequently, ~~an accurate understanding of~~ understanding the processes that control the formation and location of tidal mixing fronts, alongside an accurate knowledge of the tidal currents themselves, is necessary for effective management of economically important shelf sea ecosystems and for modelling the dispersion of tracers, contaminants and organisms.

Simpson and Hunter (1974) predict the location of tidal mixing fronts by considering surface heat fluxes and tidal stirring. They assume that surface heating is spatially uniform over the North West European Shelf, and exclude wind mixing and residual currents, to propose that ~~thermal~~ tidal mixing fronts may be found ~~along a critical contour~~ at a critical value of h/u^3, where h is the water depth and u is the amplitude of the M_2 tidal speed. We refer to this as the heating-stirring theory. No consideration is given to the influence of salinity and ~~of~~ non-tidal flows. Subsequent studies have confirmed the ~~utility of this parameter (Garrett et al., 1978; Simpson and Bowers, 1981; Bowers and Simpson, 1987); the~~ validity of this theory and the utility of the h/u^3 parameter (Garrett et al., 1978; Pingree and Griffiths, 1978; Simpson and Bowers, 1981; Bowers and Simpson, 1987). The critical value on the northwest European shelf is $\log(h/u^3)$ = 2.7 ± 0.4 (Simpson and Sharples, 1994). Later contributions added that frontal location may be expected to move as maximum tidal speeds vary over the spring-neap cycle (Simpson and Bowers, 1981; Loder and Greenberg, 1986). The local heating-stirring balance is not, however, the only control on frontal location. Salinity has been found to influence frontal location and movement in Regions of Freshwater Influence ~~(ROFI; ?)~~(ROFI; Hopkins and Polton, 2012), and ice melt water has been found to be an important component of frontal systems in the high latitudes (Schumacher et al., 1979). Furthermore, tidal straining – i.e. the shearing of the density field by the tide – can lead to a semidiurnal mixing-stratification cycle that can influence both tidal and residual circulation (Souza and Simpson, 1996; Verspecht et al., 2009; Palmer, 2010). Salinity is of clear importance in frontal dynamics, but its effect other than in ROFIs – for instance, in deeper shelf-sea regions where horizontal salinity gradients are less pronounced and in regions with a complex water mass distribution – has been less thoroughly investigated.

A ~~marked meridional mixing~~ meridional front, co-located with the path of the Fair Isle Current (FIC; Fig. 1) is present in the northwestern North Sea to the west of 1° W (Turrell et al., 1996; Sheehan et al., 2017). The front is bottom-intensified and frequently has only a limited surface signature (Hughes, 2014; Sheehan et al., 2017). Consequently, the front may be more readily observed from sub-surface observations collected from a ship or a profiling glider than in satellite observations of sea-surface temperature. The region, which is influenced by ~~a~~ cool (< 9 °C), saline (> 35.4 g kg^{-1}) water ~~mass~~ found to the east of the front (Sheehan et al., 2017; Hill et al., 2008), is characterised by features excluded from the ~~h/u^3 theoryof frontal location: there is a strong horizontal salinity gradient between fresh coastal waters and more saline, oceanic waters offshore~~ heating-stirring theory: coastal and oceanic water masses flow south into the North Sea, introducing temperature and salinity gradients that are not a consequence of heating-stirring interactions (Turrell, 1992; Hill et al., 2008; Sheehan et al., 2017), and a generally southward ~~flow~~ residual current persists throughout the year (Dooley, 1974; Turrell, 1992; Winther and Johannessen, 2006). ~~It~~ Nevertheless, it is thought that the location of the front is at least partially influenced by the local heating-stirring balance, with tidal stirring being responsible for maintaining fully mixed conditions west of the front (Svendsen et al., 1991). The hydrographic setting of this front means that its behaviour may be different from fronts where the influence of the open ocean is less pronounced.

We use high-resolution hydrographic and dive-average current (DAC) observations from a profiling ocean glider that repeatedly crossed this ~~mixing front , alongside output from a one-dimensional model to :~~ front to quantify tidal flows in the vicinity of

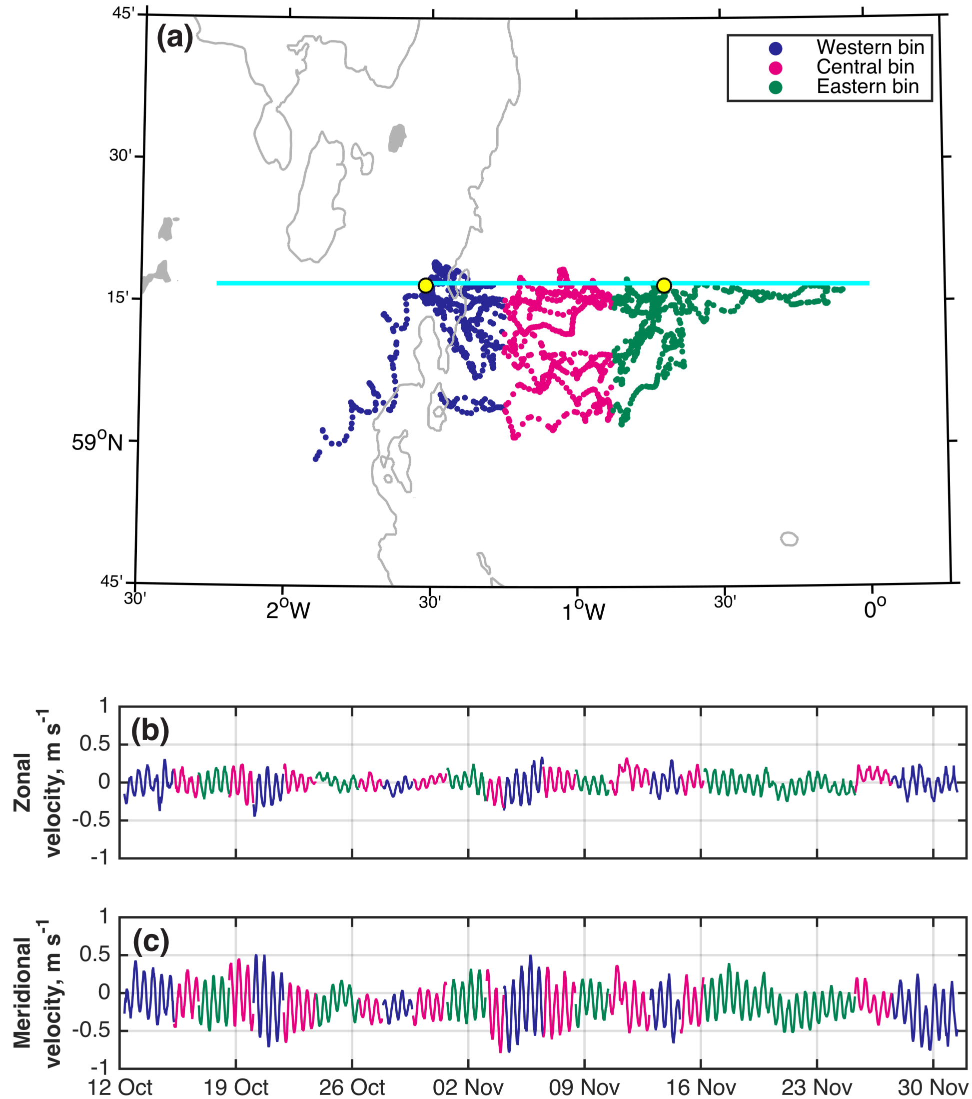

Figure 2. (a) The location of glider dives along the JONSIS section (cyan line), with dives coloured by longitudinal bin (see legend in panel a). The location of the current meters is shown by the yellow dots. The 100 m isobath is shown in grey. **(b)** Zonal and **(c)** meridional ~~dive-average current~~ DAC velocities, coloured by bin (same colour scheme as panel a).

the front~~; investigate the factors that determine frontal location; and examine the applicability of the~~ $\cancel{h/u^3}$ ~~theory to fronts in this context. The high spatial resolution of glider observations permits a more accurate estimate of frontal location than is possible from ship-based observations (e.g. Schumacher et al., 1979; Hill et al., 1997; Sheehan et al., 2017). The~~ . The DAC time series is used to accurately determine the velocities of the M_2 and S_2 tidal constituents at the time and location of each glider dive without recourse to a tide model. DAC observations are known to be accurate to within a few cm s^{-1} (Merckelbach et al., 2008), and a glider's speed through water can be determined with sufficient accuracy for gliders to measure, for example, fine-scale turbulence (e.g. Beaird et al., 2012; Fer et al., 2014). In this study, we augment this capability by demonstrating that individual DAC observations may be accurately separated into tidal and residual components. We then use these glider-derived tidal velocities, together with the ~~model output~~ output of a simple model, to investigate the influence of tidal and non-tidal processes on the location of the mixing front. The high spatial resolution of glider observations permits a more accurate estimate of frontal location than is possible from ship-based observations (e.g. Schumacher et al., 1979; Hill et al., 1997; Sheehan et al., 2017). The method for calculating tidal velocities from DAC observations, outlined in section 2, is a key result of the work with potential applications beyond that presented in section 3.

2 Glider-derived tidal velocities

~~**(a)** Tidal ellipses from glider observations (orange), current meter observations (blue) and the TPXO tide model (every fifth grid point, black). **(b)** Tidal transport ellipses, with colours as in panel a. In both panels, solid lines are for the M_2 constituent; dotted lines are for the S_2 constituent. The JONSIS section is shown in cyan, the 100 m isobath is shown in grey and land is shaded. Note that the scale of the ellipses is different in each panel.~~

~~**(a)** Zonal and **(b)** meridional velocity. **(c)** and **(d)** are zoomed-in excerpts of panels a and c respectively. The region shown in panels c and d is marked by the grey box in panels a and b respectively. In all panels, the solid black line is the M_2-S_2 tidal velocity determined from the glider observations and the dashed orange line is the M_2-S_2 tidal velocity from the sub-sampled TPXO model.~~

2.1 Method

~~During a two-month deployment (~~Between 12th October ~~–~~ and 1st December 2013~~)~~, the glider (Seaglider 502; Eriksen et al., 2001) completed 10 partial occupations of the Joint North Sea Information System (JONSIS) hydrographic section (Turrell et al., 1996). ~~The~~ Occupations took between three and 11 days, depending on how much of the section was sampled. The 127 km-long section, between 2.23° W and the prime meridian at 59.28° N (~~Figure~~Fig. 1), crosses the combined path of the two western Atlantic inflows into the northwestern North Sea: the FIC and the East Shetland Atlantic Inflow (ESAI; Fig. 1; Turrell et al., 1996). Bathymetry along the section varies between 69 and 143 m, deepening ~~offshore. All bathymetry~~ eastward. All bathymetric data used in this study were extracted from the GEBCO dataset (GEBCO_08 grid, version 20100927, www.gebco.net; resolution 30 arc-seconds). ~~Dives~~ While it is possible to estimate bathymetry from the glider's altimeter observations, we believe that bathymetry from a databank for a well-studied region such as the North Sea is likely more accurate. Glider dives were, on average, 20 minutes and 300 m apart~~, and~~ ; as one dive comprises two profiles, profiles are therefore an average of 150 m apart. Most dives sampled the full water column. DAC observations are obtained incidentally during a glider's flight as the glider is advected by the flow over the duration of a dive-climb cycle. On surfacing, the glider compares its actual, GPS-determined position with its position as estimated by dead-reckoning; the difference is attributed to advection by the DAC (Eriksen et al., 2001; Merckelbach et al., 2008). The accuracy of DAC observations was improved post-deployment by optimising the hydrodynamic model of the glider's flight (Frajka-Williams et al., 2011). DAC observations were visually inspected to ensure that there were no systematic errors due to the glider's compass calibration~~.~~, and the method described in this section was repeated using DAC observations from only east- and westbound occupations. No systematic difference between results obtained from the two samples was found, indicating that the observations are not affected by compass error.

DAC velocities were divided into three longitudinal bins along the JONSIS section (Fig. 2a), the boundaries being chosen such that each bin contained an approximately equal number of dives: 502 in the eastern bin, 514 in the central bin and 503 in the western bin. Binned velocities were treated as three discontinuous time series (Fig. 2b and c)~~located at the bin's central point. In~~ . At the central longitude of each bin, the amplitude and phase of the M_2 and S_2 tidal constituents were determined using harmonic analysis (Thomson and Emery, 2014). These results were used to construct tidal ellipses along the JONSIS section (Fig. 3). Combined M_2 and S_2 (hereafter denoted M_2+S_2) zonal and meridional velocities were then calculated at the time of each glider dive. Finally, tidal velocity was linearly interpolated ~~zonally~~ onto that dive's ~~location to construct~~ longitude to construct a time series of tidal velocity along the glider's ~~path,~~ overground track – that is, a time series of tidal velocities with data points at the time and location of each dive (Fig. 2a). These are hereafter referred to as along-track velocities (Fig. 4). Nearest-neighbour extrapolation was used for dives to the east and west of the three bins; extrapolation is necessary because some dives lie to the east and west of the central points of the eastern and western bins respectively.

The accuracy of the glider-derived ellipses, and consequently of the derived tidal currents, is dependent on the number of dives that fall within a bin, and the number of bins determines the number of points along the section at which the tide may be resolved. There is therefore a trade off between the number of constituents that can be resolved in the harmonic analysis and the spatial resolution. For a regularly spaced, continuous time series, the Rayleigh criterion ($\Delta f = 1/T$, where Δf is the difference in frequency between two constituents, and T is the length of the time series) dictates the minimum length of time series needed to separately resolve constituents of different frequencies. To resolve the M_2 and S_2 constituents from a combined signal, a time series of at least 14.8 days is needed: that is, the cycle introduced into tidal signals by the interaction of the M_2 and S_2 constituents, known as the spring-neap cycle. The Rayleigh criterion is harder to apply to a time series of irregularly spaced DAC, particularly when temporal discontinuities are introduced by the binning process (Fig. 2). Instead, setting the limits of each bin such that an equal number of dives falls in each ensures that amplitude and phase estimates are of a comparable accuracy across the section. The cumulative length of time that the glider spends in each bin is 14.6, 17.1 and 17.7 days for the western, central and eastern bin respectively, which is approximately equal to, or greater than, the minimum length of time needed to separately resolve the M_2 and S_2 constituents in a regularly spaced, continuous time series. Separating the time series into four or more bins necessarily reduces the number of dives and the length of time the glider spends in each bin. Using four or more bins resulted in S_2 ellipses with unrealistic amplitudes and inclinations, suggesting an inadequate resolution of this weaker constituent.

Two current meters were deployed on the JONSIS section for a period covering the glider deployment: an Aanderaa Seaguard single-point current meter at a depth of 40 m (1.52° W, Fig. 2a), and a Nortek AWAC profiling current meter that took measurements ~~at~~ in 4 m ~~intervals~~ bins centred from 9 to 89 m below the surface (0.70° W, Fig. 2a). Observations from the profiling current meter were depth-averaged for comparison with glider DAC. The amplitude and phase of the M_2 and S_2 tidal constituents were determined from the current meter records using the same harmonic analysis as for the glider data. ~~For comparison~~To compare the results of our method with an established alternative, estimates of M_2 and S_2 amplitude, phase and velocity, were extracted from the TPXO inverse model European shelf solution ~~(0.1° resolution; Egbert et al., 1994; Egbert and Erofeeva, 2002; Egbert et~~ the Tidal Model Driver software for Matlab (available at esr.org/research/polar-tide-models/tmd-software).

2.2 Tidal ellipses

Tidal ellipses of the glider-derived tide show a decrease in the amplitude of zonal and meridional tidal velocity with distance offshore (Fig. 3a). ~~Meridional amplitudes~~ Semi-major axes are consistently larger than ~~zonal amplitudes~~semi-minor axes, and the offshore decrease in ~~meridional amplitude~~ the magnitude of the semi-major axes is greater than the offshore decrease in ~~zonal amplitude~~semi-minor axes. The smaller rate of change in the eastern part of the section is because bathymetry gradients are smaller than in the west. Velocity amplitudes were multiplied by the mean water depth in each bin to derive ellipses of tidal transport per unit width (Fig. 3b). Compared with velocity amplitude, transport amplitude changes less markedly with distance offshore, suggesting that the greater tidal velocities observed in shallow water than in deep water are primarily a result of volume continuity rather than the exponential offshore decay of the tidal Kelvin wave.

Glider velocity ellipses compare well with velocity ellipses from the current meter observations and the TPXO model (Fig. 3a). Ellipses from ~~both~~ the three sources indicate clockwise rotation of the tide. The ellipse from the western, single-point current meter observations (Fig. 2a and 3) is likely larger (i.e. indicating faster tidal velocities) than the depth-mean glider and TPXO ellipses because tidal currents at the depth of this current meter (40 m) are less influenced by bottom friction than are depth-average velocities. Comparing glider ellipses with the TPXO ellipses at the same location, the difference between the M_2 semi-major axes is 0.10 m s^{-1} (25%) in the western bin and 0.01 m s^{-1} in the central and eastern bins (2% and 4% respectively). The difference between the M_2 semi-minor axes is 0.01 m s^{-1} in all three bins (< 1%, 8% and 15% in the western, central and eastern bins respectively). The phases of the M_2 ellipses differ by 10° ~~(<1%)~~, 7° ~~(8%)~~ and 11° ~~(15%)~~ in the western, central and eastern bins respectively. S_2 semi-major axes differ by 0.05 m s^{-1} (44%) in the western bin and by 0.01 m s^{-1} in the central and eastern bins (8% and 9% respectively). S_2 semi-minor axes differ by 0.01 m s^{-1} in all three bins (48%, 18% and 19% in the western, central and eastern bins respectively). The phases of the S_2 ellipses differ by 7° ~~(5%)~~, 2° ~~(1%)~~ and 17° ~~(11%)~~ in the western, central and eastern bins respectively. Percentage differences between the S_2 ellipses are larger in the western bin because the magnitude of the glider-derived S_2 tide is smaller than in the central and eastern bin. Differences between the ellipses in the western bin could be greater than in the central and eastern bins because the TPXO model is an inversion of satellite altimeter observations, which are less reliable near coastlines (Egbert and Erofeeva, 2002). The glider ellipses are potentially a more accurate characterisation of the tide in this part of the section.

~~The accuracy of the glider-derived ellipses is dependent on the number of dives that fall within a bin, and the number of bins determines the number of points along the section at which the tide may be resolved. There is therefore a trade off between the number of constituents that can be resolved in the harmonic analysis and the spatial resolution. For a regularly spaced, continuous time series, the Rayleigh criterion ($\Delta f = 1/T$, where Δf is the difference in frequency between two~~

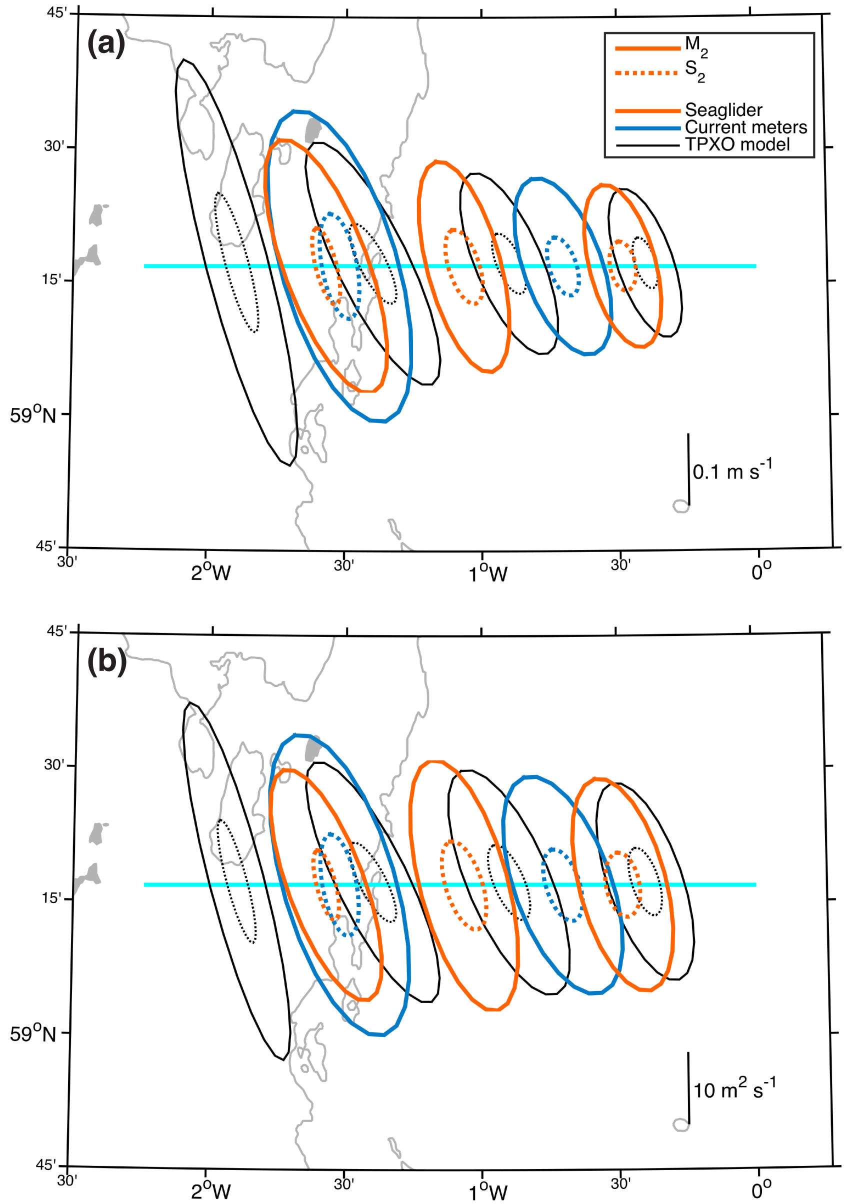

Figure 3. **(a)** Tidal ellipses from glider observations (orange), current meter observations (blue) and the TPXO tide model (every fifth grid point, black). **(b)** Tidal transport ellipses, with colours as in panel a. In both panels, solid lines are for the M_2 constituent; dotted lines are for the S_2 constituent. The JONSIS section is shown in cyan and the 100 m isobath is shown in grey. Note that the scale of the ellipses is different in each panel.

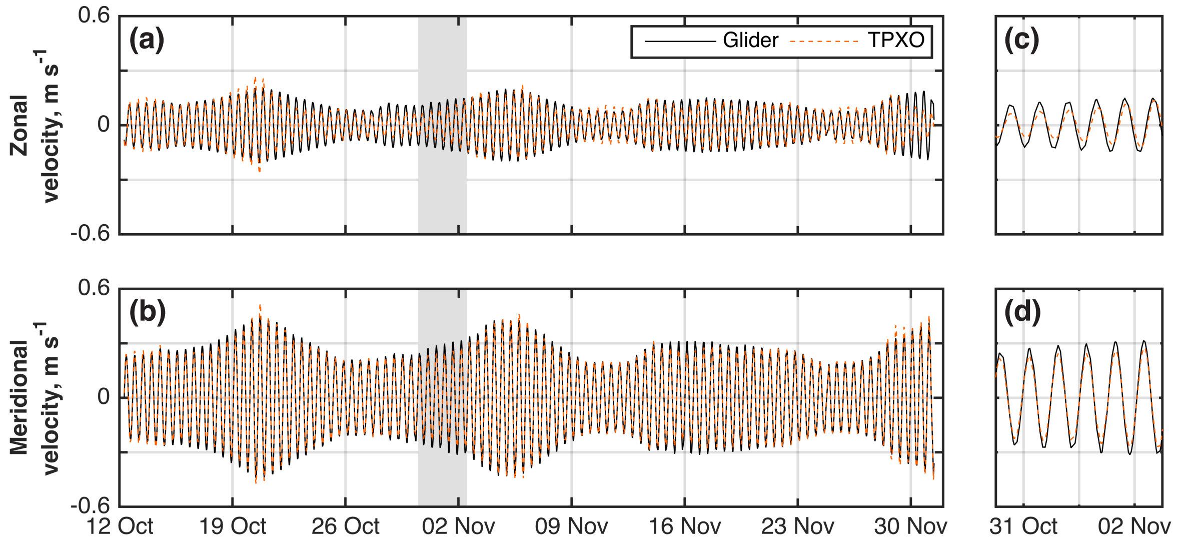

Figure 4. **(a)** Zonal and **(b)** meridional velocity. **(c)** and **(d)** are zoomed-in excerpts of panels a and c respectively. The region shown in panels c and d is marked by the grey box in panels a and b respectively. In all panels, the solid black line is the M_2+S_2 tidal velocity determined from the glider observations and the dashed orange line is the M_2+S_2 tidal velocity from the sub-sampled TPXO model.

~~constituents, and T is the length of the time series) dictates the minimum length of time series needed to separately resolve constituents of different frequencies. To resolve the M_2 and S_2 constituents from a combined signal, a time series of at least 14.8 days is needed: that is, the cycle introduced into tidal signals by the interaction of the M_2 and S_2 constituents, known as the spring-neap cycle. The Rayleigh criterion is harder to apply to a time series of irregularly spaced DAC, particularly when temporal discontinuities are introduced by the binning process (Fig. 2). Instead, setting the limits of each bin such that an equal number of dives falls in each ensures that amplitude and phase estimates are of a comparable accuracy across the section. The cumulative length of time that the glider spends in each bin is 14.6, 17.1 and 17.7 days for the western, central and eastern bin respectively, which is approximately equal to, or greater than, the minimum length of time needed to separately resolve the M_2 and S_2 constituents in a regularly spaced, continuous time series. Separating the time series into four or more bins necessarily reduces the number of dives and the length of time the glider spends in each bin. Using four or more bins resulted in S_2 ellipses with unrealistic amplitudes and inclinations, suggesting an inadequate resolution of this weaker constituent.~~

2.3 Glider-derived tidal velocities

To quantify the accuracy of the glider-derived tide (Fig. 4), the along-track M_2+S_2 velocity time series are compared with the ~~combined M_2 and~~ M_2+S_2 along-track time series from the TPXO model sampled at full resolution. Unlike the current meter observations, this model ~~, which is taken to be the best available estimate of tidal velocity,~~ provides estimates of tidal velocity across the entire JONSIS section. The root-mean-square-differences (RMSD) between the glider- and the TPXO-derived tides are 0.03 and 0.02 m s^{-1} for the zonal and meridional velocities respectively. ~~The smaller RMSD for the meridional than the zonal velocities is likely because the meridional velocities are larger and so, assuming the absolute differences between the two zonal and two meridional along-track velocity time series are comparable, the relative difference between the meridional time series will be the smaller.~~

To determine the extent to which the difference between the glider- and TPXO-derived time series may be attributed to the comparatively low resolution of the glider-derived tide, we firstly compare the fully sampled TPXO tide with the TPXO tide sampled at the same locations as the glider-derived tide (i.e. the centre of each of the three bins, Fig. 2). Velocity time series are extracted from the TPXO model at the central point of each glider bin and at the time of each glider dive. These velocities are interpolated zonally onto the location of each dive, replicating the method used to calculate the glider-derived tide. The RMSDs between the fully and sub-sampled TPXO time series are 0.04 and 0.02 m s^{-1} for the zonal and meridional velocities respectively. ~~Again, the meridional velocities are more similar than the zonal velocities.~~

Secondly, to simulate a longer glider deployment with more dives from which it would be possible to use smaller spatial bins and so increase spatial resolution, we compare the fully sampled TPXO tide with the TPXO model sub-sampled every 0.5° longitude between 2.5° W and the prime meridian. This decreases the zonal RMSD to 0.03 m s^{-1}; the meridional RMSD remains 0.02 m s^{-1}. ~~Spatial resolution is therefore an important control on the accuracy of the estimated tidal velocity; the accuracy of the~~ The spatial resolution of the glider-derived tide ~~is likely therefore dependent on the number of accurate estimates of tidal amplitude and phase that may be calculated along a section. A longer deployment that enabled the along-track DAC time series to be divided into more longitudinal bins would produce a more accurate estimate of tidal velocity.~~ appears to have little influence on the results compared with the output of a high-resolution tide model.

The ability to use glider DAC to estimate along-track tidal velocity to within ± 0.02 to 0.04 m s^{-1}, even when the tide may be resolved at only a few points along a section, could be of considerable use in regions where tide models are unreliable or unavailable, ~~further~~ enhancing the utility of gliders, for example in remote regions such as the Antarctic shelf. In order to use this method on DAC observations from other glider missions, we make the following recommendations:

1. Obtain repeat occupations of the same transect.
2. Set the transect length so as to avoid aliasing the spring-neap cycle – i.e. avoid individual occupations lasting around one or two weeks.
3. Optimise the hydrodynamic model of the glider's flight (Frajka-Williams et al., 2011) to obtain accurate DAC observations.
4. Do not attempt to resolve more constituents than may be accurately resolved given the length of each binned, discontinuous time series.

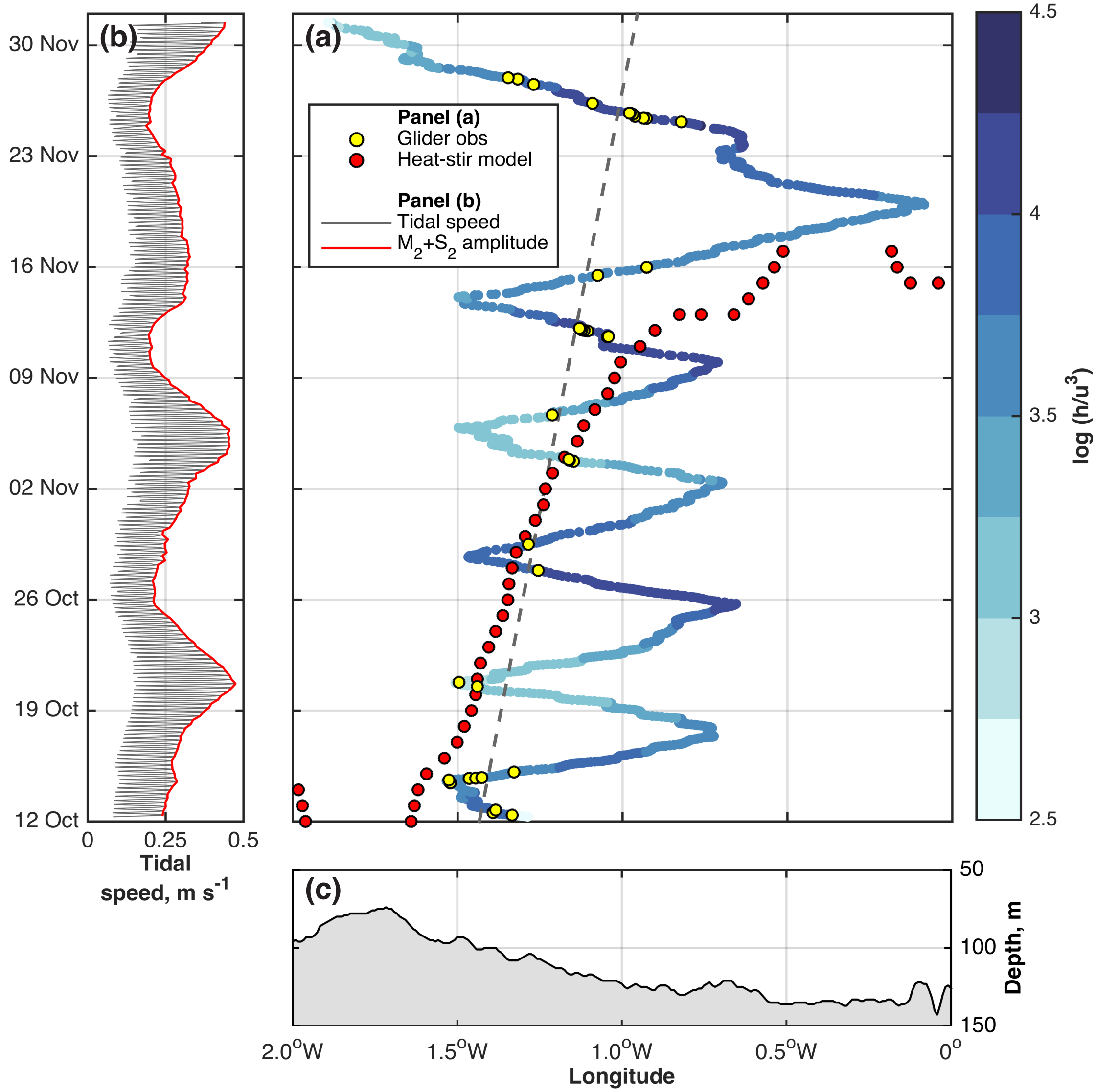

Figure 5. (a) Hovmöller plot of $\log(h/u^3)$ (colour scale) from glider observations. Yellow circles mark the observed ~~location~~ locations of the front. The dashed grey line is the line-of-best-fit through these points. Red circles mark the location of the front as modelled by the heating-stirring model. **(b)** M_2 ~~S~~+S_2 tidal speed (m s^{-1}; grey line) at the location of each glider dive as calculated using the glider-derived tidal velocities. The red line joins up the maximum speeds and is the estimate of tidal velocity amplitude, u, used to calculate $\log(h/u^3)$ in panel a. **(c)** Bathymetry (m) along the JONSIS section – i.e. h in $\log(h/u^3)$.

3 Frontal location

We ~~demonstrate the utility of the~~ apply the glider-derived tide ~~by using these tidal velocities (Fig. 4)~~ described in the previous section to study the ~~effect of tidal speed on the~~ location of a front in the northwestern North Sea. Specifically, we investigate the extent to which the location of the front may be explained by heating-stirring interactions, a principal component of which is tidal speed. Furthermore, this analysis serves as an illustration of a potential application of the method. We use TEOS-10 variables (IOC et al., 2010) in this analysis.

The location of the ~~tidal mixing front on the JONSIS section observed by the glider .~~ front as determined from the glider observations is shown in Fig. 5. The front is defined to be where the top-bottom temperature difference is 0.5° C. This definition has the advantage of being straightforward to calculate, both from observations and models, and follows the approach used in previous studies (Bowers and Simpson, 1987; Holt and Umlauf, 2008; O'Dea et al., 2012). ~~In place of the amplitude of the M_2 tidal speed, the~~ On a number of crossings of the front, the top-bottom temperature difference equals 0.5° C at several points (Fig. 5a). This is because the front often covers a zonal distance wider than that between glider dives. Observations of frontal location are not corrected for zonal tidal advection of the front. Instead, we acknowledge a zonal uncertainty in frontal position of ± 2 km (0.04° longitude), that being the mean zonal tidal displacement during the deployment.

We calculate $\log(h/u^3)$ at the time and location of each glider dive. The amplitude of tidal speed used to calculate $\log(h/u^3)$, in place of the amplitude of the M_2 tidal speed, is that of the ~~combined M_2-S_2 constituentsin order~~ M_2+S_2 constituents; this is to capture changes in tidal speed over the spring-neap cycle. The ~~combined M_2-S~~M_2+S_2 amplitude is derived from the along-track glider-derived tide: we extract a time series of the maximum speed achieved over each tidal cycle (Fig. 5b, red line) and interpolate this onto the time of each glider dive.

Values of $\log(h/u^3)$ at the front vary considerably over time (Fig. 5a), from below 3 around ~~the~~ 21st October to over 4 around ~~the~~ 12th November. Some of this range may likely be attributed to the width of the front, which can cover a range of values of $\log(h/u^3)$ at this high spatial and temporal resolution (Hughes, 2014). Often, the frontal value of $\log(h/u^3)$ lies outside the range 2.7 ± 0.4 typically used as the critical value for the northwestern European shelf region (Simpson and Sharples, 1994). However, our modified definition of the amplitude of tidal speed (i.e. M_2~~-S~~+S_2) precludes direct comparison of our values of $\log(h/u^3)$ with those previously published. Using only the M_2 tidal speed allows comparison with previous studies, although this results in a $\log(h/u^3)$ distribution that changes only spatially and that does not account for changes in the amplitude of tidal speed over the spring-neap cycle. Values of $\log(h/u^3)$ at the front when only the M_2 constituent is included (not shown) fall between 3.25 and 3.75. These M_2-only values cover a narrower range than when the S_2 constituent is included and all fall outside the range 2.7 ± 0.4.

Pingree and Griffiths (1978) note that fronts in the vicinity of the Orkney and Shetland archipelagoes are found at higher than expected values of $\log(h/u^3)$, although they modify the theory to account for bottom drag, so their values of the critical contour are not directly comparable. Salinity gradients and geographical variations in the surface heat flux are suggested as possible reasons for the deviation from predictions. Hughes (2014), using a heat flux appropriate to the northwestern North Sea, concluded from a modelling study that the critical value for frontal location in the region should be 3.4~~. This falls within~~

~~the range of values reported in this study~~; the applicability of this value was confirmed by examination of 28 years (1982 – 2008 inclusive) of satellite observations of sea-surface temperature (Hughes, 2014). The higher ~~value of the critical contour may be~~ critical value is attributed to the reduced heat flux and enhanced wind mixing at the latitudes of the northwestern North Sea compared with the latitudes of the Celtic Sea (Hughes, 2014), the site of much previous work on the h/u^3 criterion (e.g. Simpson and Hunter, 1974). ~~Consequently, our glider observations appear to confirm model-derived predictions that~~ 3.4 falls within the range of values reported in this study; our observations enable assessment of the critical value ~~of~~ derived by Hughes (2014) against full-depth observations of the front.

We acknowledge that the accuracy of $\log(h/u^3)$ ~~is location dependent, and that it falls within a wider range than previously thought – even on the northwestern European shelf for which the range 2.7 ± 0.4 was believed to be appropriate. Furthermore, the calculated values of~~ as a predictor of frontal location is greater in summer, when surface heating is the dominant control on frontal location, than it is at other times of year. However, in the absence of full-depth glider observations of the front in summer, the higher frontal values reported here appear to confirm the tendency, found in both model results and surface observations, for the front in the northwestern North Sea to be found at higher critical values of $\log(h/u^3)$ ~~point to a role for the heating-stirring balance in determining the location of the observed front, despite the front being partially the result of the confluence of the FIC and ESAI (Fig. 1).~~ than those once thought applicable to the entire northwestern European continental shelf (Simpson and Sharples, 1994). Glider observations of the front in summer are desirable.

There does not appear to be adjustment of frontal location with the spring-neap cycle, although the effects of such adjustment ~~are~~ would be much greater immediately after frontal development – i.e. in late spring and early summer (Simpson and Bowers, 1981). Furthermore, some of the additional mixing energy available at spring tides is expended reducing stored potential energy on the stratified side of the front rather than moving the front itself, limiting the extent of spring-neap frontal adjustment (Simpson and Bowers, 1981). Instead, the dominant signal in frontal location is its offshore movement over the course of the glider deployment (Fig. 5a). From a ~~starting~~ longitude of approximately 1.4° W at the start of the deployment, the front moves eastwards into deeper water, reaching approximately 1° W by the middle of November. It then widens considerably towards the end of the deployment, being spread between 1.4 and 0.8° W at the time of the final occupation ~~of the section~~(19th November – 1st December). A least-squares line of best fit through the frontal locations indicates that the front moves eastward at a rate of 0.53 ± 0.06 km day^{-1}.

3.1 Comparison with model output

~~To better understand the drivers of the observed offshore frontal movement, glider~~ We compare the observations of frontal location ~~are compared~~ with the output of ~~the simple~~a numerical model of heating-stirring processes to identify if and when heating-stirring interactions control frontal location during the deployment. We use the open-source, one-dimensional heating-stirring model of ~~Simpson and Bowers (1984) (see also Elliott and Clarke, 1991, and Simpson and Sharples, 2012).~~ Simpson and Bowers (The model is straight-forward to run; it may be readily adapted to suit the study region and to work with the glider-derived tide described in section 2; and it includes only the physical heating-stirring processes used to describe frontal location by

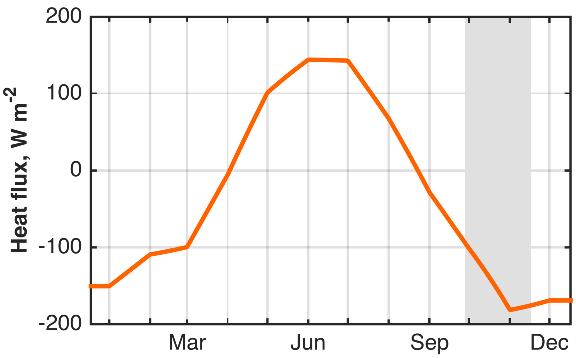

Figure 6. Total surface heat flux (i.e. the sum of latent, sensible, incoming radiative and outgoing radiative fluxes; W m^{-2}) in 2013 averaged zonally across the JONSIS section. Positive fluxes indicate energy transfer into the ocean. Latent, sensible and outgoing radiative fluxes are calculated by the heating-stirring model using the method of Sharples et al. (2006) from monthly mean meteorological parameters extracted from the NOCS Flux v2.0 dataset (National Oceanography Centre, 2008). Monthly mean incoming radiative flux is extracted from NOCS Flux v2.0. The period of the glider deployment is indicated by the grey box.

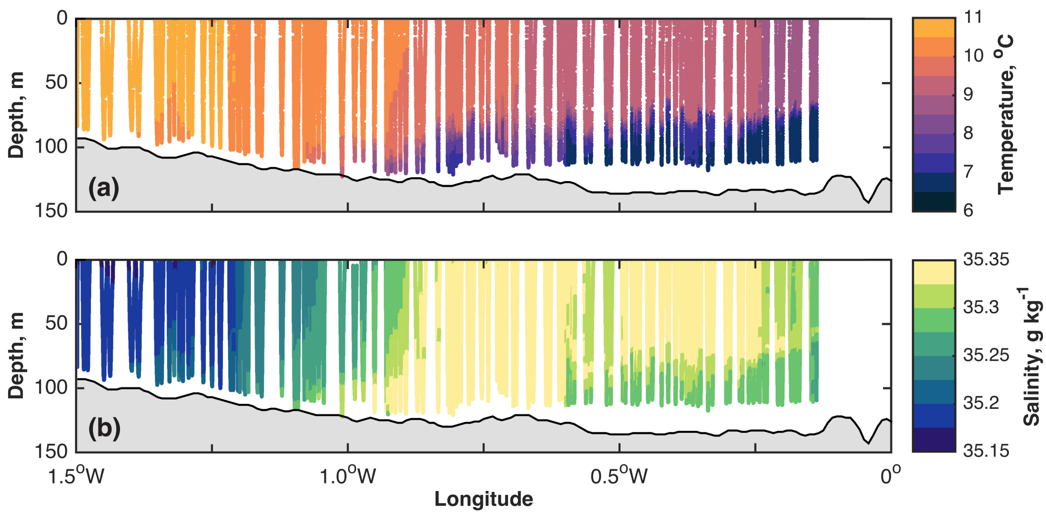

Figure 7. **(a)** Conservative temperature (°C) and **(b)** absolute salinity (g kg^{-1}) from the penultimate glider occupation of the JONSIS section (14th – 20th November 2013).

Simpson and Hunter (1974) and Simpson and Bowers (1984), and described in section 1. Consequently, the model allows us to investigate the extent to which heating-stirring interactions influence the location of the observed front (Fig. 5).

The model is forced with meteorological parameters from the NOCS Flux v2.0 data set (National Oceanography Centre, 2008; Berry and Kent, 2009, 2011) and with tidal speed~~; it~~. It simulates a temperature profile for a water column of a given depth. 55% of incoming heat energy is absorbed at the surface, the remaining 45% being distributed exponentially with depth.

This distribution is typical for coastal waters (Ivanoff, 1977). Once heat loss to the atmosphere has been extracted from the surface layer, the additional heat is mixed downwards until the increase in potential energy equals the effective stirring energy input from the wind over the given time step; the profile is then further modified by bottom-up tidal mixing until the increase in potential energy equals the effective stirring energy input from the tide. If the net surface heat flux is negative (i.e. heat loss) the model simulates convection. The new surface temperature is then used to calculate the surface heat flux for the subsequent time step (Simpson and Bowers, 1984). The original model is modified to include the improved parameterisation of heat exchange through the sea surface implemented by Sharples et al. (2006) and Hughes (2014), and to include the additional energy available for bottom-up mixing provided by a constant background flow of 0.1 m s^{-1} following the method of Hughes (2014). The magnitude of the background flow is chosen to be representative of the values observed in the region (Turrell et al., 1990; Turrell, 1992; Turrell et al., 1996). The stirring effects of a persistent background flow were not included in the original formulation of the h/u^3 theory, but the presence of Atlantic inflow in the study region makes it a necessary addition.

Temperature profiles are simulated at every 0.1° longitude along the JONSIS section and for every day of the glider deployment at daily resolution. The diurnal heating-cooling cycle is not resolved. ~~A time of representative tidal velocity is selected from the along-track time series (1st November, 14:30), and the combined M_2-S_2 zonal and meridional velocities~~ We take as the tidal speed the meridional M_2+S_2 velocity amplitude midway between spring and neap tides, and use the glider-derived tide to capture the offshore decay in tidal amplitude. Meridional M_2+S_2 velocity amplitude is calculated at the centre of ~~the three bins are determined for this time.Velocities at these three locations are~~ each bin (Fig. 2a) and is interpolated onto the ~~location~~ longitude of each model grid point~~and used to calculate the tidal speed, thus ensuring that the modelling accounts for the observed offshore decay of tidal amplitude (Fig. 3a).~~. We do not simulate the spring-neap cycle because spring-neap frontal adjustment is not observed in the glider ~~data.~~sections (Fig. 5a).

~~Total surface heat flux (i.e. the sum of latent, sensible, incoming radiative and outgoing radiative fluxes; W m^{-2}) in 2013 averaged zonally across the JONSIS section. Positive fluxes indicate energy transfer into the ocean. Latent, sensible and outgoing radiative fluxes are calculated by the heating-stirring model using the method of Sharples et al. (2006) from monthly mean meteorological parameters extracted from the NOCS Flux v2.0 dataset (National Oceanography Centre, 2008). Monthly mean incoming radiative flux is extracted from NOCS Flux v2.0. The period of the glider deployment is indicated by the grey box.~~

~~**(a)** Conservative temperature (°C) and **(b)** absolute salinity (g kg^{-1}) from the ninth glider occupation of the JONSIS section (14th – 20th November 2013).~~

Using the same definition of frontal location as used for the glider ~~data~~profiles, the heating-stirring model places the front in a similar position to the observations during the first four weeks of the deployment (Fig. 5a), albeit approximately 0.1° further west prior to ~~the~~ 15th October. The coastal front that appears in the far west of the section between ~~the~~ 12th and 14th October is not considered here because it is outside the longitudinal range of the glider ~~data. The~~ sections. We test the sensitivity of the results to the speed of the background flow~~has little influence on frontal location while~~. Modifying the background flow ~~is slower than 0.1 m s^{-1}. At speeds greater than 0.1~~ speed by ± 0.03 m s^{-1}, ~~increases in background flow speed have an ever greater effect on frontal location, pushing it eastwards into deeper water and causing it to decay earlier. No front~~

~~forms in the heating-stirring model during the period of the glider deployment at for background flow speeds in excess of 0.31 m s-1~~a reasonable range, makes no difference to the results at the bottom of the range, and shifts the front by approximately 0.05° longitude (3 km) eastward at the top of the range.

The similarity between the heating-stirring model (with a realistic background current of 0.1 m s^{-1} and an intermediate tidal amplitude) and the observations during the first four weeks of the glider deployment suggests that the interaction between surface heat fluxes and tidal mixing explains the location of the front during this period. Specifically, the negative surface heat flux (i.e. heat loss to the atmosphere) during the period of the ~~glided~~ glider deployment (Fig. 6) means that stratification is maintained only by heat remaining in the water column after the period of summer heating (April to September; Fig. 6). As heat is progressively lost to the atmosphere, the influence of tidal stirring becomes ~~every~~ ever more dominant, pushing the front into deeper water (Fig. 5). However, the persistence of the observed front after ~~the~~ 17th November 2013 and its slower easterly advance compared with that of the modelled front (1.59 ± 0.08 km day^{-1}; ~~this~~ rate excludes the secondary front that emerges on ~~the~~ 15th November 2013 around 0.1° W), suggests that the heating-stirring balance is not the primary control on frontal location in the latter period of the glider deployment (i.e. after approximately ~~the~~ 4th November).

3.2 Comparison with observations

~~To understand the controls on frontal location in the latter period~~ The existence of the front in the observations despite its disappearance in the heating-stirring model suggests that processes other than heating-stirring interactions are responsible for maintaining the front into the latter weeks of the glider deployment~~, we examine temperature and salinity observations from the glider . A thermal front , located between 0.6 and 0.9° W (~~. In addition to the horizontal temperature gradient observed by the glider on its final two crossings of the front (observations from the penultimate crossing are shown in Fig. 7~~a) , is co-located with~~) a horizontal salinity gradient exists between the relatively fresh ~~coastal water~~ waters in the west ~~and the more saline water offshore (Fig. 7b). This pattern is typical for the JONSIS section in autumn (Sheehan et al., 2017). The heating-stirring model does not simulate this cool, saline water mass. It is not produced by heating-stirring interactions but instead has its temperature set when the water column is fully mixed during the preceding winter, before it is isolated under the thermocline at the onset of stratification (Svendsen et al., 1991; Turrell, 1992; Hill et al., 2008). Additionally, the~~ of the section and the relatively saline waters in the east. Salinity is a useful water mass tracer in the region and permits identification of the water masses present in the observations. The salinity-minimum (< 35.25 g kg^{-1}) to the west of the section is indicative of coastal water from around Scotland, which is freshened by river input and runoff (Dooley, 1974; Turrell et al., 1992); the salinity maximum (> 35.25 g kg^{-1}) to the east of the section is indicative of water of recent Atlantic origin (Turrell et al., 1992). Intermediate salinity (~35.275 g kg^{-1}) and minimum temperature (< 7.5° C) is indicative of water that has spent the previous summer isolated beneath the seasonal thermocline (Svendsen et al., 1991; Turrell et al., 1992; Hill et al., 2008); this has been called Cooled Atlantic Water (CAW; Turrell et al., 1992). The southward penetration of Atlantic water from the open northern boundary of the North Sea elevates ~~offshore salinity in the region~~ the salinity of CAW (Hill et al., 2008). The ~~thermal and haline buoyancy introduced by this water mass sustain the front beyond the time of year at which~~ heating-stirring ~~interactions would sustain the front. As the water column progressively cools throughout the late autumn and winter, removing the thermal signal~~

~~of the front ,~~ model cannot reproduce these water masses: they are not formed locally by heating-stirring interactions and their distribution in the northern North Sea is controlled by advection. The temperature distribution created by these water masses is such that a horizontal temperature gradient is maintained. In particular, the bottom front, which is the most dynamically significant feature of the ~~salinity gradient remains, meaning that frontal dynamics – for instance, along-frontal jets – influence the region throughout the year (Sheehan et al., 2017).~~ frontal system (Hill et al., 2008; Sheehan et al., 2017) is maintained by the presence of the Atlantic-influenced CAW.

The glider observations presented in Figs. 5 and 7 demonstrate that a front can exist in the northwestern North Sea independently of heating-stirring interactions. Such a front is clearly not simply a tidal mixing front. However, during the first part of the deployment, the observed frontal location compares well to frontal location as predicted from consideration of only heating-stirring interactions. We propose that the observed front is a hybrid between a tidal mixing front and a front ~~that~~ which forms due to ~~the advection of two different water masses . During summer, the front's location is principally determined by the surface heat fluxes and tidal mixing according to the mechanism originally proposed by Simpson and Hunter (1974). It is likely that this period coincides with the time during which the surface heat flux (Fig. 6) is positive. Outside of~~ horizontal gradients between adjacent water masses in a region of complex water mass interaction. In winter, in the absence of local solar heating and when temperature variation between water masses is negligible, there exists a salinity front in the region that gives rise to thermohaline flow (Sheehan et al., 2017). In summer, we propose that local heating-stirring interactions modify the water masses to the extent that the front is moved to a position as predicted by consideration of heating-stirring interactions. The present study does not include observations of the front at this time, ~~i.e. during the winter and early spring, the location of~~ but when forced with an annual cycle of multi-decadal mean meteorological values, the heating-stirring model places a tidal mixing front at approximately 1.5° W in summer; the front is ~~principally determined by the zonal extent of the cool, saline Atlantic-origin water. The glider observations presented above~~ found at the same location in multi-decadal summertime averages of JONSIS section hydrography (Sheehan et al., 2017). The observations presented in this study (Fig. 5a) capture the period ~~during which the front transitions~~ in the annual cycle when, in 2013, the front makes the transition from being a ~~tidal mixing front governed by local~~ front controlled by heating-stirring interactions ~~, to being governed by the location of two distinct~~ to being a front controlled by the distribution of water masses.

4 Summary

~~Glider~~ We have demonstrated that glider DAC observations may be used to determine tidal velocities at the time and location of each glider dive to within $\pm$ 0.04 m s^{-1}. ~~The glider-derived~~ Glider-derived tidal velocities compare favourably to output from current meters and the TPXO tide model~~sampled at the time and location of each glider dive, and particularly well to output from the model when sampled at the centre of each bin used in the calculation of the glider-derived tide~~. The method enhances the utility of gliders as an ocean-observing platform, particularly in regions such as Antarctica where tide models are known to be ~~limited.~~ poorly constrained. The method could also be extended to two dimensions: for instance, to two gliders flown along parallel transects, or to one or more gliders flown in a butterfly pattern. A longer deployment than the two-month deployment presented in this study would allow for more tidal constituents to be resolved from the resulting DAC time series.

Glider-derived tidal velocities were applied to study the location of a ~~tidal mixing~~ front in the northwestern North Sea. The results of a one-dimensional heating-stirring model, and comparison of these results with ~~glider~~ the glider's hydrographic observations, demonstrated that salinity gradients and the distribution of water masses are important controls on frontal location in the region, in addition to surface heating and primarily tidally induced mixing. ~~The~~ A water mass distribution exists which gives rise to a frontal boundary in temperature and salinity. In the absence of significant surface heating, this is the primary source of a frontal boundary and therefore the primary control on frontal location. In summer, heating-stirring ~~balance is likely the principal control in spring and summer; salinity gradients and water mass extent are likely the principal controls in autumn and winter. An open question is how the advection of buoyancy influences the front during the summer: specifically, whether it dampens spring-neap frontal adjustment.~~ interactions modify the water masses, enhancing the background temperature gradient such that heating-stirring interactions become the primary control on frontal location. This situation persists until the autumn: the observations presented in this study capture the period during which, in 2013, the front transitions from being primarily a tidal mixing front to being primarily a front between different water masses. The interannual variability of the timing of this transition is a topic for further investigation.

Water mass distribution and attendant spatial gradients of thermal and haline buoyancy are likely to be important in shelf ~~sea~~ seas where significant incursions of oceanic water are found, such as the northwestern North Sea, the South China Sea (Shaw, 1991; Su, 2004), along the eastern coast of the United States (Blanton et al., 1981) and around Antarctica (Moffat et al., 2009). ~~Mixing~~ While heating-stirring interactions are ubiquitous in shelf seas, fronts in such regions may persist during periods when local heating-stirring interactions would not promote frontal formation. Consequently, controls on frontal location may change over an annual cycle. Given the thermohaline flows commonly associated with shelf sea fronts, and given the influence that fronts have on the distribution of physical and biogeochemical properties (Turrell, 1992; Hill et al., 2008), this has important implications for the dynamics, ecology and management of shelf sea regions.

Data availability. The glider data used in this study are archived at the British Oceanographic Data Centre.

Competing interests. The authors declare that they have no competing interests.

Acknowledgements. PMFS was funded by NERC CASE PhD studentship NE/L009242/1 awarded to UEA and Marine Scotland Science. ~~SG502~~ Seaglider 502 was owned and maintained by the UEA Marine Support Facility. We thank the scientists and crew of MRV Scotia for the glider deployment, and the scientists and crew of MPV Jura for the recovery. We are grateful for financial support from NERC for

the deployment as a demonstration for UK-IMON. Glider data were processed using the UEA Glider Toolbox (Queste, 2013, available at bitbucket.org/bastienqueste/uea-seaglider-toolbox).

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