Response to Ocean Science Discussion:
https://doi.org/10.5194/os-2020-112-RC1, 2021
Authors reply in bold.

General Comments:

This paper makes a good contribution to the field of seismic oceanography and presents interesting and useful analyses of 3D seismic data. The writing and figures are of a high quality. **Thank you for acknowledging our contribution and the quality of our paper.**

I recommend Major Revisions as I have a number of comments. Most of my comments can be easily addressed. However, I do feel that this paper could benefit from a change of focus. Please see my comment below: **Thank you for providing valuable suggestions to us. We have implemented your comments and revised the manuscript.**

The paper is written in such a way that it is not immediately clear what the benefit is to an oceanographer. As you know, seismic oceanography is simply a tool that we can use to learn about the ocean. So, I think this paper could benefit from some re-direction toward the oceanographic aspects of its findings. **We have enhanced the oceanographic aspects of the findings in the revision (throughout Sections 2, 3, and 4).** In particular: - In the Introduction, there is little description of the oceanographic setting. What is it and what do you expect to see/resolve with seismic oceanography? Adding a paragraph along these lines would help place your findings in context later on. **We have revised the introduction to clarify our goal and expectation (Lines 54-59).** - In Section 3, you describe some seismic images in different orientations (i.e. inline, crossline, depth slices). Are the observations you describe typical across the survey? **There are no typical observations, as our seismic inline images may look very diverse as they are from different periods of time. Our choice of images has been clarified (e.g., Lines 171, 182, 194-195).** If so, can you comment further on what oceanographic implications these images have. **We have commented on the oceanographic implications in the revised manuscript (e.g., Lines 178-181, 183-186, 193, 200-204, 349-362).** For example, are the discontinuities in the crossline direction caused by heave of water masses? **Yes, the heaving can cause discontinuities in our crossline images (Lines 183-184).** What sort of mixing processes could cause the degradation in Figure 5. **The possible mixing processes are discussed in Lines 348-361.** Section 3 is presented as a way to guide the reader through the meaning of the images, but I think you could present them as some results (particularly if the images in Figs 5-7 are representative). **We now present Section 3 as some oceanographic results, but we are very conservative here to avoid giving arbitrary interpretations.** Please see some related suggestions in ‘Specific Comments’. - The discussion is dominated by seismic acquisition and processing thoughts. However, you could

make some interesting discussion points about the oceanography related to Section 3 and 4. **We add some discussion about the oceanography throughout Section 3 and 4.** The authors may have a future paper that will address some of these points, and I understand that it is difficult to conclusively interpret seismic data without concurrent hydrographic information. Nevertheless, I think that the paper would be more impactful and have a wider scope if the authors address this general comment. **Thank you for understanding the difficulty of interpreting seismic data. Yes, we are writing a paper on internal wave variations in this region, with in-depth spectral analysis of seismic images and estimation of diapycnal diffusivity, combining satellite sea surface height and geostrophic currents. This is too much to include and beyond the scope of this paper, which is to explore fundamental features of oceanic 3D seismic volume. However, we respect your comments, and add discussion of ocean dynamics in Lines 348-361.**

Specific Comments:

Introduction: - In the Introduction, I think you should set up the expectation for this paper more clearly. For example, something like Line 331 would be useful at the end of the Introduction. **We have revised the end of the introduction to clarify the expectation (Line 54-67).** - You (correctly) mention a few times that 3D seismic oceanography is not well-developed. However, I think it would be fair to devote a few sentences to the seismic oceanography studies that have used 3D data, and to what end, in the Introduction (I see they are signposted in the Discussion). As far as I am aware, these 3D studies are: (i) Gunn et al., (2020) who showed the evolution of a front, (ii) Dickinson et al., (2020) who explored the passage of an eddy, and (iii) Blacic and Holbrook (2010). **We have briefly reviewed these 3D seismic oceanography studies in our revised manuscript (Lines 45-46, 52-53).**

3D Seismic Processing - Why does the velocity model have to be calibrated with the CTDs and in what way did you do this calibration? **The CTD casts were used to improve the RMS velocity model building since they are high-resolution data and are helpful for quality control of velocity model building. In this sense, the CTD is used as guidance for the manual picking of the semblance panels.** In my experience, the seismic derived sound speed models are poor when there is some unknown in the acquisition geometry (e.g. stretch in the streamer). Is that the case here? Another sentence to explain further would be useful. **Yes. We also excluded far-traces with offsets greater than 4000 m for processing/imaging to reduce the effect of long-offset deviations on the data preprocessing and velocity model building (added in Line 84-85).** - You do not mention deconvolution in this section. I suspect it was too computationally expensive to apply? It would be good to describe what each reflection is in a bit more detail for those that are unfamiliar with seismic imagery (insert somewhere around Line 104). Then if you did/did not apply deconvolution becomes important for this description.

We have excluded deconvolution from our preprocessing workflow since our initial deconvolution tests were not satisfactory and reliable (being too expensive was also a minor cause). We now explain seismic reflection for those that are unfamiliar with seismic imagery in Lines 113-114.

3D Seismic Volume - I understand your point about using the inline and crossline terms. However, can you add in a sentence about how the survey is orientated with regards to the oceanographic context. From the inset of Figure 1, the survey is a bit too far north of the Loop Current. Do you expect this section to have high eddy-kinetic energy or be quiescent? Perhaps it should be mentioned somewhere that you are in a continental slope setting. **We have added the description of the oceanography context including the water dynamics in our seismic location (Line 68-72), and information regarding inline and crossline orientation (Line 117-118).**

Understanding 3D Seismic Water Column Images. - The observations you describe in this section are interesting and warrant further discussion here. Can you explain these qualitative observations further and link them with your inferences in Section 4.2? **We have added the explanation for the observations in Section 3 and further discuss them in the Discussion.** o Paragraph 2: I think that your observations are very interesting. Can you speculate on what might be driving the mixing of the water column? **Discussed in Lines 349-262.** What are the typical processes in this area? **Mentioned in Lines 350-352.** o Paragraph 3: Again, this is very interesting. Can you expand on how you interpret these discontinuities? Heaving of the isotherms? Tides? **Expended in Lines 183-186.** Heaving can be more prevalent at different depths, so may explain why the discontinuities are not constant as a function of depth. **The timescale of the deep ocean is generally longer than that of the surface ocean, causing discontinuities being less significant at deeper depths. Heaving is a possible cause here. Revised in Line 183-184.** o Paragraph 4: Again, an interesting observation. Can you comment on what this suggests in terms of timescales? **Commented in Lines 200-204.**

Theoretical Analysis - This thought experiment is useful, however I am not sure what you are trying to get at given your empirical analysis in Section 4.2. You mention the high-frequency aliasing in Lines 261-262, but that is your only direct comparison between the two sections. Perhaps adding a few sentences to explain the purpose of this section in more detail, or removing it and expanding and improving upon Section 4.2? **Our theoretical analysis is to use a simple (single-frequency) theoretical example to understand the temporal variation (now explained in Line 210), while our empirical analysis resolve the complex variations in our 3D seismic volume (now explained in Lines 247-248).**

Empirical Analysis - Your cross-correlation analysis is very interesting; however the structure of this section is confusing and I think you need further explanation and

quantification in some places. **We revised this section based on your following comments (Lines 245-290).** o You define the terms ‘inline variation’ and ‘crossline variation’, but then do not use them very often. You could use them in some places in the main text which would make the writing sharper (e.g. Line 260). **We have moved the term definition to Line 216-217 and reused them throughout the section.** o After the equation, can you include the portion about 1D and 2D cross-correlation (i.e. Line 236-242). Following that, can you describe what these cross-correlations mean (i.e. Lines 230-235). Finally, discuss the results of Figure 9 and 10. **We have revised this section following your suggested structure (see Line 245-290).** o Having read this section a number of times, I am confused by why there is no temporal variation in 9a. Does the cross-correlation not compare multiple inlines that are separated by a few hours? **We have updated Fig. 9 by adding illustrations for how to derive inline and crossline variations and corresponding text (Line 252-254). There is no temporal variation in Fig. 9a/c because the inline variation compares multiple crossline sections. Temporal variation appears in Fig. 9b/d because crossline variation compares multiple inline sections that are separated by a few hours.** I think the description in Line 236-242 could be clarified by removing the use of alternating brackets to describe two things in the same sentence, e.g. ‘inline (crossline)..’, and by including some descriptive examples. **We have removed the brackets and revised this part (Line 253-254).** o What is the level of noise here? **The signal-to-noise ratio (SNR) of our seismic images is ranging from 8-10 (using the formula of Ruddick, 2013).** Are you sure some of the fluctuations in 9a are real? **We believe our results are correct.** What is a significant R value here? **There are no significant R values here. The correlation function measures the fluctuation.** Can you include an uncertainty and/or level of significance on Fig 9? **We cannot add uncertainty or significance analysis to Fig. 9 because the correlation function analysis is not statistics based. It only quantifies the fluctuation.** o Line 250-252: I’m not sure I follow this conclusion from Figure 9. I agree with you, but not based on Figure 9. **We have revised this part (Lines 288-289).** Furthermore, I think you should specify that the lack of temporal variation in the inline direction is specific to this region, as this conclusion will not be relevant everywhere (also specify at Line 264). **We have limited our conclusions to within our seismic volume (Line 279). However, please kindly allow us to explain our thoughts. As far as we know, seismic vessels are often surveying with the velocity of 2-3 m/s, which is much faster than the movement of mesoscale ocean structures such as eddies, fronts, and internal waves. Therefore, there is not much temporal variation in the surveying line (i.e., inline direction). But in the crossline direction, there must be significant temporal variations because of the vessel special moving (e.g., zigzag) patterns. The bottom line is the temporal variation is always way more significant in the crossline direction compared to the inline direction. Thus, this is the case in any 3D marine seismic data, not just our data set.** The reason there is little temporal variation in the inline direction here is because of the setting of the seismic survey with respect to the oceanographic context. **Agreed.**

Discussion - The discussion is coming from a seismic point of view, there is little discussion of the oceanography. Please see my general comment. **We added a new paragraph to discuss the oceanography (Lines 348-361).**

Figures - Figure 1 is excellent. It might be useful to add the average time between each inline on the figure, as you mention the temporal aspect several times in the main text. However, this change is up to the authors. **Thank you for your suggestion. However, we kept Fig. 1 unchanged, because the time between inline is complicated (see Fig. 4).** Figure 2. In this figure, you have the vertical resolution as 5 m, but in the text you mention 6-7 m. Whichever it is, be consistent. **Revised as 6-7 m in Fig. 2 caption.** Figures 5-7: Interesting figures. Are they representative? Why did you choose them? If they are typical, you could replace 'example' with 'representative'. **They are not always representative. We have explained our reason of choice in the corresponding text.** Figure 9-10: Can you add some indication of the uncertainty? **We are not able to add the uncertainty here because the correlation function analysis is neither a prediction, nor a measurement, and people usually do not give the uncertainty for the correlation function analysis.**

Technical Corrections:
Line 7: missing 'the' before 'crossline direction' **Corrected.**
Line 9: delete 'allow to'. **Deleted.**
Line 29: not sure if 'indeed' is necessary. **Deleted.**
Line 30: change 'primary' to 'and are primarily' **Corrected.**
Line 31: the placing of the commas makes the sentence sound weird. How about 'This new cross-discipline, between . . ... oceanography,. . ..'. Or start a new sentence after 'known as seismic oceanography'. **A comma added in front of the word "between".**
Line 101: I am not familiar with the term 'chair cut display'. Do you mean the display in Fig. 2? If so, please can you add a signpost to Fig. 2 at the end of this sentence. **Figure 2 is not shown in the chair-cut display. Sorry for the confusion. We have removed this term.**
Line 109: 'water columns' sounds a bit odd. What about 'shows only the portion of the water column below 200 m'? **Revised.**
Line 112: please be more specific about the average hours between the inlines. **Revised.**
Line 115-116: Great sentence. **Thanks.**
Line 136: Do you need a new paragraph here? **Paragraphs combined.**
Line 138: You could delete 'Again' before 'We emphasize' **Deleted.**
Line 143: You could just cite Klaeschen, as you have already given the name of the assumption earlier. **Revised.**
Line 150: the 'indeed' chops up the sentence. I would delete. **Deleted.**
Line 151: missing 'to' after 'We refer'. **Added.**

Line 124: You do not use ‘i’ in the equation, just 1 and 0. ‘i’ and ‘i+1’ in the equation would be useful. Also, I think the ‘medium’ at the end of the sentence should be ‘layer’. **Corrected.**
Line 154: delete ‘here’ before ‘we present’ **Deleted.**
Line 161: I would delete the ‘mostly, but not completely’. I believe you are trying to say that it is temperature and salinity gradient that controls the reflections. However, by stating this caveat now, you make the latter part of the sentence weaker. Can you re-word slightly so that the conclusion (i.e. the change is real, not an artefact) is clear? I suggest removing this caveat entirely, as you explain a few sentences later. **Revised.** Line 162: delete ‘the acquisition’ and ‘an’. **Deleted.**
Line 163: ‘amplitude of seismic reflection is’ should be ‘amplitude of seismic reflections are’. **Corrected.**
Line 165: Colon should be a full stop. **Corrected.**
Line 167: Why is there emphasis on ‘time-varying’. I think this is either obvious, or may need more explanation if I am not following your meaning. **Emphasis removed.**
Line 177: I would change ‘at shallow. . . deep one’ to ‘in shallower portions of the water column’. **Revised.**
Line 178: I would delete ‘the seafloor is associated . . .scale and’ as I do not think it is necessary to state. Then the sentence would be ‘. . .because there is no temporal variation. . .’ **Revised.**
Line 182: replace the second ‘representation’ with ‘view’. **Replaced.**
Line 182: Missing ‘a’ between ‘observe similar’ **Added.**
Line 183: delete ‘the’ before discontinuity. **Deleted.**
Line 200: missing ‘a’ before ‘1-km inline’ and ‘1-km crossline’ **Added.**
Line 205: replace ‘being’ with ‘the’. **Replaced.**
Line 228: ‘note’ rather than ‘noted’. **Corrected.**
L231-232: I think the sentence needs a bit of re-wording, something like ‘The obtained cross-correlation is plotted as a function of spatial distance and temporal shift’. **Revised.**
Line 232: ‘correlation lengthscale’ is more common in the literature I believe. **We did not make any changes here, as the “correlation length” in a concept related to correlation function:**
https://en.wikipedia.org/wiki/Correlation_function_(statistical_mechanics).
Line 246: ‘dominated’ not ‘dominant’ **Corrected.**
Line 248: again, ‘correlation lengthscale’ **Unchanged. See reasons above.**
Line 250: I disagree that the inline direction is ‘only’ associated with spatial variation. How about ‘mostly’? **Revised.**
Line 255: The sentence starting ‘This decreasing trend’ is unfinished. **Revised.** Line 266-268: A good point to state here. You cannot be expected to interpret every single thing. **Thanks.**
Line 293-294: Can you replace the first set of brackets with commas to avoid the double bracketing? **Replaced.**

Thank you for all your valuable comments.

Response to Ocean Science Discussion:
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Authors reply in bold.

In this paper, from a 3D multichannel seismic survey acquired for oil and gas exploration in the Gulf of Mexico over six months period, a 3D water-column seismic volume was derived. Furtherly the paper analyses the differences of information provided by inline sections and crossline sections. It is useful for promoting 2D seismic oceanography methods to 3D seismic oceanography ones. **Thank you for acknowledging the value of our work. We aim to promote understanding of the temporal and spatial variations of ocean 3D seismic volume, which is fundamental in 3D seismic oceanography.** The problem is that example data used in the paper is not so meaningful. There are no obvious ocean features such as eddy, internal wave, front, staircases, etc. observed in the seismic sections or slices. It is suggested to do further analyses or change the example data, such that we can get new information from cross-discipline studies. Physical oceanography implications are expected to be demonstrated after major revision. **Thank you for raising your concerns to us. The data and analysis here is meant for the temporal and spatial variation of the water column in general. Nevertheless, we have clarified that variations of thermohaline structures and internal waves above the continental slope (e.g., Fig. 5; Lines 178-181), which are caused by an eddy approaching the continental slope (Lines 348-361). The further analysis of the internal wave variation will be in another paper.**
We have also enhanced the oceanographic implications by making interpretation of ocean structures (e.g., Lines 178-180, 183-184, 200-204), and added a discussion of the occurred mesoscale ocean dynamics (Lines 348-361). We hope you will support our manuscript based on our clarification and improvement. Thank you.