

Response to RC2

Please find the reviewer's comments in blue and our replies in black.

This study applies an unsupervised classification technique, called profile classification model (PCM), to a profile data set in the Weddell Sea region. The authors highlight the importance of this technique as a powerful tool to identify spatially coherent structures in poorly observed regions, such as the Weddell Sea, in addition to other analysis techniques. Without any given spatial information, the PCM identified four spatially coherent classes: 1) circumpolar, 2) transition, 3) gyre edge and 4) gyre core, with sometimes overlapping but distinct properties of temperature and salinity for each class.

The authors emphasize that the PCM is able to reproduce expected structures from previous studies, but is also able to shine light on more subtle thermohaline structures in previously under-appreciated locations in the Weddell Gyre region.

The manuscript provides an interesting approach and a powerful technique to investigate thermohaline structures in poorly observed regions. The method is applicable to other branches of climate science and is thus a valuable contribution to the climate science community.

Thank you for your thoughtful and detailed response. We have attempted to address your comments below, and we hope that you find the revised manuscript to be improved and suitable for publication.

Before I recommend this study to be accepted for publication, I would like to see an updated version where specific concerns and questions have been addressed and modified.

Specific comments:

The manuscript would benefit from changes to the structure throughout. In some places the manuscript is quite repetitive, whereas in other places there is not enough discussion with previous literature. I think this is related to the large number of subsections (17 in total) in the manuscript that interrupt the flow and make it very difficult to follow at times. I suggest merging some of the subsections to increase readability and avoid repetition:

We apologise that you found the manuscript frustrating to read at times. With great respect to the reviewer, the use of repetition and subsections was very much intentional, and we would argue that both style elements are appropriate and suitable for how our intended audience is likely to engage with this paper. Our audience likely tends to read papers online, skipping around the paper and only skimming those sections that they find of interest. It is written with the casual reader in mind. The casual reader will hop around the paper, skim

sections, and look for take-home messages. Clearly-labelled subsections and repetition will help them navigate and understand the paper.

That being said, we took your feedback to mean that the paper's flow needed to be improved. As such, we did attempt to adapt the paper in specific ways following some of your suggestions. We sincerely appreciate the level of in-depth consideration that you gave this work; we took your suggestions seriously.

For example, we did eliminate one of the unnecessary subsection headers in the introduction in order to help it flow more smoothly. We decided to keep the methods-based subsection header (now 1.1) to clearly demarcate the circulation-based material from the methods-based material. We merged two of the discussion subsections that were both relevant to the WSC. We kept the rest of the subsections in the results and the discussion section for the reasons mentioned above. Overall, we also tried to make the subsection headings more informative and the transitions between subsections smoother. We hope that you find our revised paper to be an improvement in terms of readability.

[Introduction: I suggest merging the subsection 1.1 and 1.2 in order to strengthen the storyline for the reader to follow. Simply, stating that this region is poorly observed is not strong enough.](#)

We agree that the transition between these two subsections was too abrupt. Although we have kept the subsections for reasons mentioned above, we have attempted to make the transition to what is now subsection 1.1 a bit smoother.

[Note that many scientists are not familiar with PCM, so I suggest introducing it first, before giving a literature review of which publications have used this method.](#)

Yes, we agree that this section needed a bit more of an introduction to machine learning in general. The first four paragraphs of subsection 1.1 proceed from the more general to more specific. The first paragraph introduces unsupervised learning in general before citing a few recent oceanographic regime discovery applications. Here, the inputs/features are not necessarily profiles - they are terms of a steady-state budget equation or The second paragraph introduces the concept of profile classification, before citing a study that does this using self-organising maps. The third paragraph introduces PCM, and the fourth paragraph is a literature review of PCM applications in oceanography. We have modified this section to hopefully improve its clarity.

What specific questions are the authors going to address? What has not been investigated before? What is PCM and why using it? What is the aim of this study?

We apply the PCM technique to this newly-curated Weddell Gyre dataset to identify coherent regimes in temperature and salinity structure in this region, with the aim of refining our understanding of the area and generating new hypotheses for further investigation. This has not been done before because (1) the datasets have been too small until recently and (2) unsupervised classification techniques have not been used very much in oceanography until recent years. PCM is suitable for this application because it robustly and automatically groups profiles together into classes, allowing for the identification of coherent regimes in thermohaline structure, in a probabilistic fashion. We have added some text to the introduction that will hopefully clarify our aims and why we chose PCM.

Data and Methods: This section is quite repetitive. I suggest merging the subsections to avoid repetition. Can you elaborate more on how you use PCA to reduce the dimensionality? Or at least refer to the supplementary material if not discussed in the text?

Again with great respect, we believe that the subsections and repetition make it easier for the casual reader to navigate around the paper. Subsection 2.1 covers the dataset and how it was processed, and subsection 2.2 covers the PCM technique in more detail than had been given in the introduction. We would argue that this is a logical separation.

That being said, we completely agree that there was not enough detail about PCA. We have referred the reader to the supplementary materials (now Appendix A) for further details about how we used PCA.

There is an entire paragraph on the difficulty of classification as it becomes less interpretable the more complexity is added to the classes? Rather than explaining possible options can you specifically state how you overcame this issue?

In our view, this is a crucial paragraph. We wish to draw attention to this aspect of selecting the number of classes, especially for those who may wish to use this method or unsupervised classification in general. It is not only a technical issue to be overcome in our specific case: it is a general usage consideration for the entire field to be aware of, especially those who wish to use this technique with their data.

2: The label font sizes are inconsistent. a) The colorbar is not labelled. Does the colorbar indicate the number of profiles you have for each location? Why 2° latitude-longitude bins when you use 1° bins later on?

The font size inconsistency has been fixed in the new version of Figure 2. Yes, we totally agree that it makes more sense to use 1° bins throughout the paper – this has also been changed.

What are the advantages and disadvantages of the PCM overall?

PCM allows for the robust classification of profiles into profile types with very little prior input from the user. It also uses probabilistic information that can be further exploited to quantify boundaries between classes in a novel way. We have added some text to the introduction which hopefully clarifies this.

Results and Discussion: It is very difficult to jump between discussion and results due to the large number of subsections. I think the results and discussion would benefit from one another if they would be merged. Merging results and discussion avoids repetition, but also maintains readability and provides the ability for the reader to logically order the results and how this compares to previous studies.

We apologise that you found it difficult to navigate the manuscript. As discussed above, and emphasising again our great respect, our use of subsections and repetition is very much intentional. We have purposefully used the structure where one presents the key results in the results section and the limitations, wider context, and other aspects for consideration in the discussion section. Again, we again thank the reviewer for many specific, helpful suggestions, which we have attempted to incorporate into our revised manuscript.

A contour plot or similar would be really helpful to highlight where the classes overlap.

We experimented with different ways to plot the classes and where they overlap, but we did not find a plotting method that produced a visually clear result. We hope that showing the full spatial extent of the classes, together with the fronts, coastlines, and f/H contours will make it possible to compare the spatial distributions of the classes.

L210-229: This paragraph contains a lot of speculation (lots of 'may') and would benefit from comparison to previous studies for justification. Are these results expected? Is it comparable to previous studies? What are the novel findings?

Yes, we agree that this comparison was a bit minimal in the previous version. We have revised this section to reference other studies and to highlight which of the findings might be considered novel, or at least which findings might be considered useful refinements of our understanding.

L244-246: This sentence is very unclear to me. Are you indicating that a large I-metric suggests regions of increased mixing or a transformation in profile types or both? Please clarify.

Apologies for the confusion. We have changed this to "mixing and transformation between profile types", as we did mean both.

L247-250: Can you specify what a low I-metric indicates?

Yes, we have added a bit more detail here as to what a low I-metric indicates in this context.

Furthermore, the authors emphasise that PCM highlights both expected and underappreciated structures and is thus a helpful tool to develop new research questions and hypotheses. It is unclear which structures are expected and which are novel or previously underappreciated. Which new findings did this method provide and which additional analysis steps are suggested to investigate the novel findings in more detail?

Yes, R1 had a similar comment. We agree that this was unclear in the original draft. On further reflection, we removed the somewhat subjective phrase “expected and underappreciated structures” from the manuscript, since expectations and appreciation may vary between researchers, depending on their particular expertise. However, we have attempted to better emphasise how our results compare with current understanding (see the revised results and discussion sections). In particular, there is now a summary of key refinements to current understanding near the start of the discussion section.

The authors further discussed seasonal variations within each class specifically with respect to vertical profiles and Theta-S diagrams. Did you also consider seasonal variations in mixed layer depth, signatures of WW (temperature minimum), signatures of CDW (temperature maximum) and how those vary spatially within the classes?

Thank you for this suggestion. We had not examined the spatial variation in the class properties by season, but we agree that this is an important consideration. As mentioned in our response to RC1, we have expanded the “4_seasonal_analysis” Jupyter notebook to include seasonal plots. We found that the seasonal cycle for each class displayed relatively little spatial variability, with a few key exceptions:

Quantity	Class	Note
MLD	Circumpolar	Summertime values shallower in western part of domain
All	Transition	CDW intrusion most apparent in summer and autumn, partly due to seasonal bias in sampling
MLD	Gyre core	Winter and spring values especially deep in the south
Depth of PT max	Circumpolar	Summer and autumn values are shallower in western part of domain away from the Antarctic Peninsula, corresponding to lower latitudes
Depth of PT min	Circumpolar	North-south contrast in depth is especially apparent in winter and spring, i.e. shallower depths at higher latitudes as expected. Winter water is shallower at higher latitudes and deeper at lower latitudes
Depth of PT min	Transition and Gyre edge	Especially deep summertime and springtime values in the western part of the domain

Overall, the spatial structure of the seasonal cycle mostly highlights the gradients already seen in the climatological average. We have added a paragraph and a new figure on this topic in section 3.5.

How did you deal with the varying number of profiles per season (less profiles in winter months)? How robust are the results?

We agree that the seasonal bias in sampling is a limitation of our current method. We discuss this in subsection 4.6 in the paper. Overall, because we are trying to build a climatological picture of the Weddell Gyre region, we do not expect this bias to drastically alter our results. However, this is clearly an area where further investigation would be useful.

Minor comments:

Suggest removing preambles in all sections as they are mostly repetition to the manuscript structure you have already introduced in the introduction.

The preambles help orient readers who may be jumping around and skimming the paper. As mentioned above, we are writing with the casual reader in mind.

Adjust spelling as required by ocean sciences (British or American spelling not both)

We have attempted to use British spelling throughout. That being said, the lead author is hopelessly mixed in a blend of the two spellings. Although we have attempted to be consistent in this new version, we trust that the copyediting process will catch any remaining spelling oversights.

L3, L4, L23: Can you define extremely? Suggest giving values here.

We have removed the “extremely” from L3. In terms of L4, we think that “extremely remote” is clear from context. For L23, the phrase “below the surface freezing point” provides context.

Suggest adding more information on how this method is valuable to the wider community in the abstract.

We have made the last sentence of the abstract a bit more general and have added a bit more detail. Specifically, we have revised this to state that “PCM offers a useful complement to existing expertise-driven approaches for characterising the physical configuration and variability of oceanographic regions, helping to identify coherent thermohaline structures and the boundaries between them.”

L84-96: This is just a list of references who have used PCM before. How is this relevant to this study? Note that at this point you have not introduced the method yet.

The paragraph preceding the original L84-96 introduces PCM in a conceptual way. We feel that the introduction is an appropriate place to discuss other studies that have deployed PCM, specifically because each one has pushed the frontiers of what is possible with this method. Along with each study, we mention the specific innovation delivered by that paper, which is relevant to the developing maturity of PCM as a technique. In addition, we hope that this paper will be read by those who may be interested in trying PCM. For those readers, a survey of recent applications is useful.

L96-99: Is additional motivation that PCM can be used to redefine boundaries and fronts? You don't mention it again? It would be really interesting if you could elaborate more on that.

Yes, we discuss this again in subsection 3.2. We have revised the subsection title to better signpost this work.

L189: Define Winter Water

Done

L208-209: How much does it deepen the further you go away from the gyre core?

Reporting the 25th, 50th, and 75th percentiles, the winter water depths range from (20m, 60m, 80m) in the gyre core, (20m, 80m, 100m) in the gyre edge, (60m, 80m, 120m) in the transition class, and (100m, 120m, 140m) in the circumpolar class. We have added these values to the text.

L221-223: Can you elaborate more on why these are indicators of e.g. Weddell-Scotia Confluence waters? Is this new information? Is this comparable to previous studies?

Yes, we believe that the revised subsection 4.3 makes this a bit clearer.

L247-262: Can you refer to the Figs. And subplots here?

Yes, thanks for catching this oversight. Added.

Equations B1 and B2. Define K.

Done, thanks for catching this omission. These equations, along with the definition for K, are now in Appendix A.

Figure comments

Overall, I suggest using different colormaps for Figures, showing different variables. Consider changing the colormaps to increase contrast between contours and increase visibility.

We make heavy use of the “cmocean” colormaps for oceanography because they are perceptually uniform (Thyng et al., 2016). We also use the “cividis” colormap for sequential data because it is also perceptually uniform, in addition to being colorblind friendly. Other options that we tried were considerably worse or were inappropriate for sequential data. We note that our colormap choices were tested electronically.

Fig 1: Can you describe the choice of arrow colors on this map? Did you choose the colors based on temperature? If so, why do CDW and WDW have the same color? On a printed version you can barely see the arrows underneath the geographic locations added to the Fig. I suggest moving the all geographic locations labelled in the Fig. outside to achieve a clear view. Further the font size of the x- and y-axis labels needs to be increased.

The original color scheme for the arrows was not based on temperature and was arbitrarily chosen solely for visual separation. However, we have made revisions by using a colour scheme recommended by colorbrewer2.org. We chose a 4-class diverging colour scheme that is colorblind safe, print-friendly, and photocopy safe. We kept the original ASF colour, but the new scheme should provide better visibility and clarity.

We apologise for the text boxes' opacity not producing the desired effect in the printed version of the paper. We intended for the semi-transparent boxes to allow the text to stand out without blocking the arrows completely. We have addressed this issue by repositioning the text boxes to improve clarity.

Additionally, we have increased the font size of the axis labels to improve readability.

3: In section 3.1 you discuss the differences between each identified class. You specifically mention the median depth of the temperature minimum. I suggest adding the median depth as a horizontal line to each class to visually highlight the differences in each class.

The median depth of the temperature minimum does not vary enough between the classes to be visually distinct on the scale of Fig. 3. However, on Fig. 3 we have added dotted lines to indicate, for each class, the median depth of the temperature maximum.

In addition, as described in our response to RC1, we have changed the way in which we select and plot the individual profiles for Figs. 3 and 10, leading to more consistent visibility across the subplots.

On Figs. 4, 5, 6, 7, 8 the grey lines are hardly visible. Suggest using a darker shade of grey and thickening the lines. I also suggest using a different colormap for each variable to visually differentiate between the plots. The blue is very dominating, so other structures are very hard to see.

We apologise that you found the grey lines to be hardly visible – is the author referring to the print version? They appear to be suitable on the electronic version, as far as we can tell. We intended the grey lines to be a visually “weak” element of the figures, providing a little dynamical context without overwhelming the other visual elements. We experimented increasing the line thickness and darkening the colours, but doing so causes the figures to become visually messy and hard to read. Should the article be accepted in OS, we will seek advice from the copyediting team on which line thickness and colour will achieve good visual results in both the print and electronic versions.

As mentioned above, we make heavy use of the “cividis” colormap because it is colorblind friendly, perceptually uniform, and sequential.

Figs. 7 and 8. Figures are much too small. Labels are too small.

Configuring these two plots is certainly a design challenge. We wish to have the depths and values plotted side-by-side for comparison; this works okay for the electronic version, because readers can zoom in as needed. But we agree that this makes them too small in the print version. If this article is accepted, we trust that the typesetting service will help us resolve this design challenge, perhaps by allowing these two figures to be rotated where they take up an entire page.

Figs. 9. You are using conservative temperature. Shouldn't it be Θ -S diagrams? Suggest changing this throughout.

Yes, thank you for catching this. Changed throughout.

Fig. 11 The background is too dark. I cannot read the isopycnal labels (much too small, contrast too low)

The background is the lowest value of the “cividis” colorbar that we wish to use due to it being colorblind friendly and perceptually uniform. However, we hope that you find the revised Fig. 11 to be improved. The revised figure now features:

- Larger x-axis and y-axis labels
- Larger x-axis and y-axis tick labels
- A single enlarged colorbar for the entire figure, instead of several smaller, identical colorbars
- Bigger colorbar tick labels and a bigger colorbar label
- Grey contours have been replaced with white contours for better contrast

Fig. 12. Suggest labeling the colorbars. In b) suggest adjusting the colormap. It is really hard to see the sea ice freezing line.

Yes, good suggestions, thank you. Done.

Reference

Thyng, K. M., Greene, C. A., Hetland, R. D., Zimmerle, H. M., & DiMarco, S. F. (2016). True colors of oceanography. *Oceanography*, 29(3), 10