Authors' response to Review No 2

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First, we would like to thank the reviewer for their helpful and detailed feedback on our manuscript. The additional questions and enquiries helped us to improve the quality of the text and further our understanding of the different processes and their connections. In the following, we answer the reviewers' comments in turn in blue. New text added to the manuscript or modified from the original manuscript appears in *italics*.

Main comments

I have 2 main comments on the V shape metrics that could bring more robustness to the manuscript:

1. What are the robustness of your results to the choices made in your definition? Is it possible, based on your algorithm to define the maximum depth of the V-shape (or the thickness of the V shape) by applying it to multiple depth? This could support some discussion points of your manuscript and give a more complete understanding of the variability of the V shape structure.

    The algorithm is best applied in depths were the V-shape of the isopycnals is not intersected by the continental shelf. At the sill of the Filchner Trough, this is the case down to approx. 600 m, less in the surroundings. To avoid significant interactions with the mixed layer near the surface, we also apply the algorithm only below 200 m. Between 200 and 600 m, the GOC is robust against depth selection, which is not the case above and below this depth interval. As can be seen in Fig. C1, the upper 200 m show distinct seasonal variability in GOC. Below 200 m, the algorithm detects events with low GOC over multiple model layers, even though the strength of detected events varies (Fig. C1b). While the algorithm can also be applied to deeper layers, this is not insightful without additional information on the existence of the on-shore arm of the V-shape. The algorithm has no criterium for the existence of the V-shape, but instead searches for the density minimum in a plane, explaining why we restrict its application to between 200 and 600 m where we know the V-shape exists. Given the definition of the GOC, it is not possible to define a maximum depth of the V-shape based on the GOC at multiple depths. To achieve this, an additional criterium is needed to test if the minimum was found at a boundary node. If that is the case, the isopycnals do not have the characteristic V-shape. By adding this second parameter (V-shape: yes/no), the GOC could give a more comprehensive understanding of the dynamic and stability of the V-shape. We amended the following paragraph in the discussion of the GOC: *The introduction of* *the GOC provides a metric for the stability of the ASF in areas of cross-slope transport in dense-shelf areas. However, not all features of the V-shape of the density distribution are included in its definition. Because it searches for density minima at a chosen depths, inferring the existence of the complete V-shaped distribution is not possible from the GOC alone. This information needs to be compiled before applying the algorithm. The GOC is useful to detect strong changes in the cross-slope density distribution that remove the dip in the isopycnals completely or lead to a lateral displacement of the V-shape in a section parallel to the continental slope. However, the GOC is not able to differentiate between a lot of small displacements that just exceed the distance threshold* d_L *and few, large displacements. The selection of* d_L *as a maximum displacement threshold also influences the result. A distance larger than ten times the grid size reduces the number of recognised events by 12.5% compared to a* d_L *of two times the grid size; with* d_L *100 times the grid size, the number of recognised events decreases by 29.1%. Additionally, the GOC is sensitive to the chosen depth. Generally, the GOC is robust against depth selection within the water column below the mixed layer but above the depth of the continental shelf to prevent an intersection of the isopycnals with the sea floor within the V-shape. To minimize the impact of seasonal variability in the upper ocean and to avoid an intersection of the chosen depth layer with the continental slope within the main feature of the V-shape, a depth of 250 m was chosen for this study.*

2. About the processes, based on your introduction the present day V-shape structure is mostly driven by the cascading of the DSW. After the regime shift, you mention that there is still a V-shape structure but at shallower depth and without DSW cascading. What is the processes that maintained the V-shape without the entrainment of the overlying surface water to the descending flow? And can you put that in relation with region that already experimented a regime shift like the Amundsen Sea and as far as I know, don't have a V-shape (even weak) in the range you mentioned here for 2100.

   The continued presence of the on-shore arm of the V-shaped density distri-

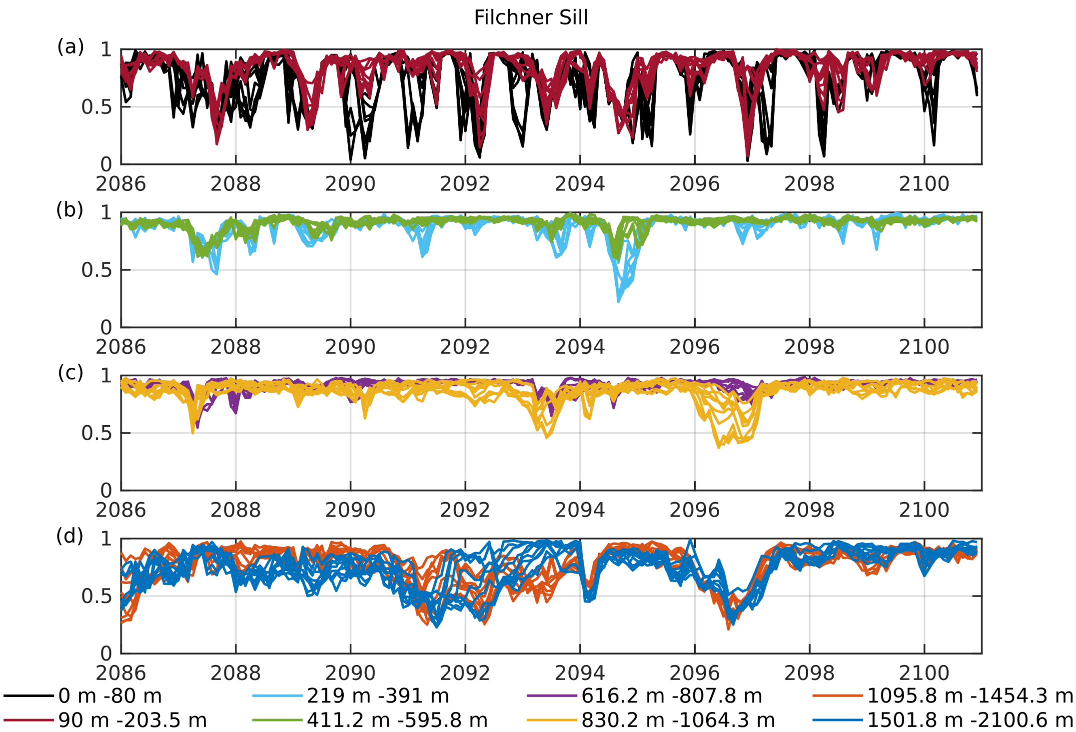

Figure C1: GOC in REF at different layer depths.

bution in the upper layers even after the regime shift in FECO is a result of two processes. The sea ice formation in winter, while strongly reduced compared to the beginning of the century, leads to the formation of DSW. This DSW has a lower density at the end of the century, but is exported from the continental shelf (Fig. 11c of the manuscript). In the upper ocean, the DSW on the continental shelf presents a barrier for the Ekman transport against which surface water is pushed and subducted. The difference to the beginning of the simulation/21st century lies in the depth to which the surface water is subducted. While the transport of mWDW creates, at first glance, a picture similar to that of a warm shelf of Amundsen Sea (Thompson et al., 2018), the presence of the V-shape in the density of the upper layers presents a distinct difference. Atmospheric wind patterns like the Amundsen Sea Low or the Bellinghausen Sea Low create a more variable surface wind forcing (Turner et al., 2013), removing the mechanism for the formation of the off-shore arm of the V-shape. Additionally, the warm shelf regions are not areas of DSW formation, therefore removing the other mechanism that leads to the formation of the distinct V-shape in the density distribution at the continental slope. We added the following text to the discussion to highlight these aspects: *The warming of the Filchner Trough through increased heat transport creates a warm shelf that, in some parts, resembles the warm shelf in the Amundsen Sea (Thompson et al. 2018). The exception is the continued presence of the V-shape in the density distribution of the upper ocean at Filchner Trough. Atmospheric patterns like the Amundsen Sea Low create a more variable surface wind (Turner et al., 2013), and the absence of DSW formation on the shelves of the Amundsen Sea remove the mechanisms for the formation of the V-shaped density distribution.*

Specific comments

Section 1

l76-l83: I think, 'section' instead of 'chapter' should be used.

Done.

l76-l83: You described well what you will present in section 3.2, 3.3, 3.4 and 3.5. It is worth adding a line on section 2 and section 4 for completeness.

The paragraph has been extended: *A brief description of the models and the methods used for analysis are given in Section 2, all results will be discussed in Section 4.*

Section 2

Section 2.1

l86-l96: what is the bathymetry source? What eddy parametrisation are you using? What bulk formulation for the atmospheric flux?

To answer these questions, the following has been added to the method section of the manuscript: *The model utilizes the ocean bathymetry, ice shelf geometry and grounding line position from RTopo-2 (Schaffer et al. 2016). Parametrizations of* *subgrid-scale fluxes use the Gent and McWilliams (1990) scheme and Redi (1982) rotated tracer diffusion. Further detail on parameterizations in FESOM-1.4 has been provided by Wang et al. (2014). Bulk formulae for momentum transfer between the atmosphere and the ocean/sea-ice surface are quadratic functions of the velocity difference. The drag coefficient and the transfer coefficients for latent and sensible heat fluxes vary as a function of stability following Large and Yeager (2004).*

l90-l91: It is not clear to me the resolution. You mention 4km around ice shelf cavities and 25km at 75S. It is unclear to me because there is cavities around and northward than 75S.

The numbers are specifically given for the Weddell Sea. We specified this in the text as follows: *The variable horizontal resolution of the ocean mesh ranges from (minimum) 4 km around Antarctica and its adjacent ice shelf cavities, via 25 km at 75°S in the open ocean in the Weddell Sea, to 250 km at the equator.*

l93: can you mention the vertical resolution range? For example at the surface and 1000m depth.

The vertical resolution decreases with depth. While the grid has a spacing of the layers of 5 m in the upper 100 m of the water column, at 1000 m the layer are separated by 30 m. The layer thickness increases up to 337.5 m at nearly 6000 m depth. The information has been added to the text: *In the vertical, the mesh has 99 depth levels (z-levels) of varying increasing thickness with depth, spanning between 5 m near the surface, up to 337.5 m at nearly 6000 m depth (Gurses et al., 2019; Nissen et al., 2023).*

Section 2.2

l110: Do you know the possible impact of atmospheric forcing produced by model in 'forecast mode'? Could it impact the solution?

Due to the short simulation times of 12 hours spin-up and one day before reinitialization, the CCLM results remain close to the forcing data set of AWI-CM output which is used to constrain the model at its outer boundaries. It is impossible for CCLM to drift far away from its forcing, and tendencies arising in these short simulation chunks cannot accumulate. Whether this is a strength or a weakness of the concept may be debatable; we see it as a strength because it emphasizes local and resolution effects rather than larger-scale model physics differences. Initial adjustment processes at each of the restarts, on the other hand, are removed by ignoring the first 12 hours of CCLM simulation.

l110: A brief description of the performance of CCLM on representing present day Antarctica climate and comparison with the two well know Antarctic regional model RACMO and MAR is welcome.

In response to this comment, the following paragraph has been added to the manuscript: *CCLM was evaluated for the present days climate for the Weddell Sea region in Zentek and Heinemann (2020) using near-surface data, upper-air data, ERA reanalyses (ERA-Interim and ERA5) and the Antarctic Mesoscale Prediction System (AMPS, Powers et al. 2012) for the period 2002–2016. CCLM showed a good representation of temperature and wind for the Weddell Sea region.*

Section 2.3

l133: Could you explain why 250m and not another depth? How robust are your conclusion to a change in this choice? In your figure 2a, depending of what depth I choose, I can have variation of about 0.5 degree in latitude. If we look at fig. 2b, most of your points are with a 0.5 degree latitude band. Therefore, I am wondering the robustness of the result about meridional change/deplacement of the front.

The depth of 250 m was chosen based on the depth of the continental shelf and to reduce the influence of seasonally changing surface water. The chosen plane does not interface with the ocean floor and cross-sections show that the V-shape exists at this depth, which might not be the case at greater depths (see also explanation above). While the position of the V-shape can vary, the absolute position is not part of the calculation for the GOC, only the relative distances between neighbouring density minima. A meridional shift of the complete V-shape does therefore not influence the result of the GOC. This information has been added to the text: *Because the algorithm only includes the relative distance between the density minima, the GOC is robust against horizontal displacement of*

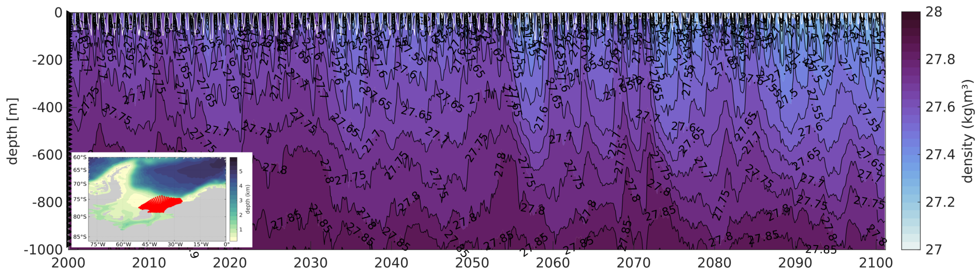

Figure C2: Hovmöller diagram of the monthly mean density relative to 1000 kg/m^3 in the wider Filchner Trough area (see map) in REF. The white line shows the mixed layer depth.

the whole V-shaped density structure.

l133: Is 250m an issue with the winter mixed layer? Is the 250 m depth line within or below the mixed layer depth?

The winter mixed layer depth is underestimated by the model (Fig. C2). As a result, 250 m is below the mixed layer for the majority of the time. If the GOC was affected by the winter mixed layer depth, we would expect a clear seasonal decrease in the value, which is only the case for the upper approx. 200 m of the water column (Fig. C1a). Additionally, we found only weak or no correlation between the export of DSW from the shelf an the GOC, indicating that also increased export in winter or spring does not have a strong impact on the GOC.

no specific line: Based on your algorithm, if you applied it at each depth level, could you define the vertical extent of the V-shape and latitude variability in depth of the V shape position to complete your analysis and add robustness to some affirmation.

At greater depth, the isopycnal intersects the continental slope, and the on-shore arm of the V-shape is (probably) missing. The GOC can't differentiate between a minimum in a V and a minimum of a sloping plane. It its current form, the GOC can not be used to define the vertical extent of the V-shape (see also response to main comment).

Section 3

Section 3.1

obs comparison: I would like to see a discussion on the realism of the shelf properties, V-shape and offshore properties with respect to observations on the present period for REF and FECO simulations. This will bring more confidence in your results.

The circulation patterns on and off the continental shelf are well represented (see also Fig. S1 in the Supplements) by the model. The salinity of the shelf water is generally lower in the model results than in observations. The temperature on the continental shelf is up to 0.6°C warmer in the model results than in observations. The largest differences in the temperature between model and observations can be found in the area of the highly variable mWDW current entering the continental shelf. The following comparison to observational data has been added to the manuscript: *Generally, the circulation in REF on and off the continental shelf are well represented by the model. Comparison to observations from mooring and CTD data (Schröder, 2010; Schröder et al., 2014, 2016, 2019; Janout et al., 2019) show that the salinity on the continental shelf is slightly underestimated by the model results by up to 0.15 psu (Fig. S13b), however some areas in particular in Filchner Trough can overestimate the salinity slightly. The temperature on the on the shelf is up to 1°C warmer in the model than in observations (Fig. S13a), but largest differences in the temperature can be found at the eastern slope of the Filchner Trough where the highly variable mWDW current flows onto the continental shelf. At the continental slope, the temperature difference can be larger, while the mWDW transported by the ASC is colder by up to 0.5°C. FECO produces a similar temperature distribution as REF (Fig. S14a), but produces lower salinity values (Fig. S14b).*

l159: I found the sentence hard to follow when looking at Fig. S1a as this is not a temperature map.

The figure refers to the transport patterns on the shelf, not the temperature distribution. The warm water filling the Larsen Ice Shelf cavity can also be seen in Fig. 3d. We added a figure reference and reworded the sentence to: *In addition,* *mWDW at temperatures around -1°C can be found on the continental Shelf and in the Larsen Ice Shelf cavity (Fig. 3c, d). This water mass originates from Ronne Trough and follows the coast northward (Fig. S1a).*

Section 3.2

l166: Fig. S3 called before S2.

Done.

l168: About the 'smaller amplitude', can you give a number?

The thermocline can change depth by up to 100 m over the course of one year according to Hattermann et al. (2018). The paragraph has been amended as follows to include this information: *The seasonality is consistent with observed variations in the thermocline depth at the Filchner Trough sill, though the variation is low compared to the amplitude of over 100 m observed (Hattermann, 2018).*

Figure 3: Can you make it bigger? Maybe in a 2x2 panel with grid lines?

We adjusted the figure.

l177: There is no observations in Fig. S4. Reformulate.

Done.

l178: Clarify what you call DSW export in Fig. S6 because Fig. S6 show meridional and zonal velocity without indication of density. Furthermore, right south of the cross, there is a wall of one pixel. This let suggest, that what you call DSW export is not the southward transport of the bottom cell. You should add a clear definition of what you call DSW and make it more visible in Fig. S6 and in all the other figure you discuss DSW.

We selected the maximum meridional velocity as export velocity at the indicated location, because comparison between Fig. S6 and Fig. 4 of the main manuscript shows the dense water in this position. For clarification, we added some isopycnals to Fig. S6 and corrected some numbers.

l179: I found hard to understand the 'weakened Ekman downwelling' with your temperature and salinity hovmuller in Figure 7. Can you plot a more direct variable like the Ekman pumping for example?

Positive surface stress curl corresponds to Ekman downwelling on the southern hemisphere. This is visible in Fig. 6. Fig. 7 was wrongly referenced and has been corrected.

Section 3.3

Fig. 5 and 4: Bigger (maybe 2x2?) and with the same size (I have the feeling that when you added the legend it shrink the panel vertically in Fig. 5 wrt Fig 4).

Done.

l191: What isopycnal are you using to affirm that. Is it still valid if you used another isopycnal?

As can be seen in Fig. 4 and Fig. 5, we look at the 27.7 and 27.55 isopycnals because they lie at similar depths and (nearly) don't interface the surface. The statement is also true for other isopycnals.

Fig. 5: Why do you color a different isopycnal in Fig. 5 compared to Fig. 3 and 4? Maybe also homogenise the color. For exemple the 27.8 is black in Fig3 and white in Fig4?

The 27.7 isopycnal does not show the V-shape at the end of the century. Instead it intersects with the continental slope, similar to the 27.8 isopycnal. The placement (2x2) and colours have been adjusted.

l190: You mention that the depth of the V shape is reduced by using the 27.8 isopycnal. Why using 27.8 to compute the depth of the V shape when in 2100 time slice, there is no left arm and so no V shape with this isopycnal?

We used the 27.8 isopycnal because we chose a density that does not intersect the surface to isolate our analysis somewhat from changes in the mixed layer. It is also not a characteristic of this particular isopycnal, but rather of the whole V-shape. Additionally, even though at the end of the century the 27.8 isopycnal terminates at the continental slope, vertical movement propagates through large parts of the water column, and the isopycnal needs to be consistent to compare the beginning and the end of the century. It is possible that we underestimate the movement by choosing an isopycnal that is not part of the 'real' V-shape at the end of the century, but this should not affect our results.

l200: Can you clarify the 80%. On Fig S7b, a reduction of 80% should lead to 40 cm

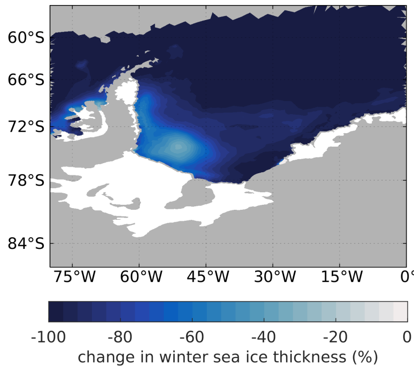

Figure C3: Change in sea ice thickness between the 15-year means of 2086-2100 and 2014-2000 in REF.

thickness in 2100 (2 m in 2000).

The time series shown in Fig. S7 shows the annual average sea ice thickness over the continental shelf of the southern Weddell Sea. However, thickness varies greatly between the Ronne and Filchner sections, with much greater sea ice thickness being reached in the Ronne sector of the continental shelf. The thicker the ice, the more can melt. To be more precise, the winter sea ice reduces at least by 35% between the 15-year mean of 2000 to 2014 and the 15-year mean 2086 to 2100 (Fig. C3). We have clarified this in the text: *With a reduction of winter sea-ice thickness by at least 35% - in large areas even more - compared to the beginning of the century, some of the up - and downwelling areas are redistributed.*

Section 3.4

Fig. S8: add grid on the figure

Done.

Section 3.6

l263: I don't really understand. Can you reformulate the bloc discussing Fig. 8c. It is not clear what to look at.

The on-shore arm of the V-shape in FECO is only very weakly pronounced after the mWDW bottom-current onset (Fig. 8d). The isopycnals above the continental shelf also show no seasonal variation in depth or form. In REF, the density distribution on the continental shelf leads to the formation of the typical V-shape (Fig. 8c). The isopycnals above the continental shelf also experience stronger seasonal depth variations, which might be caused by their shallower position closer or in the mixed surface layer. The paragraph in the manuscript has been reworked as follows: *Visible as a sudden increase in the average temperature in the Filchner Trough (Fig.* **??** *c), and as a layer of warm water at the bottom of the Filchner Trough (Fig. 8d), the inflow of mWDW in FECO in 2093 brings the bottom density in the Filchner Trough closer to that of the ASC. This has the effect of increasing the stratification of the water column. In combination with low sea-ice formation rates and reduced mixing (not shown) during the freezing season, the seasonal variations in the southern arm of the V-shape vanish at depths below approx. 450 m (Fig.* **??** *d). In REF, the density distribution on the continental shelf leads to the formation of the typical V-shape (Fig.* **??** *c). The isopycnals above the continental shelf also experience stronger seasonal depth variations due to the location closer or in the mixed layer. Seasonal variations of the depth and position of the V-shape and the position of the northern arm can be found in FECO and REF. The on-shore arm of the V-shape in FECO decreases strongly in vertical extent. From a height difference in spring of approx. 200 m between the deepest point of the V-shape and the shallowest point above the continental shelf, the 27.4 kg m^{-3} isopycnal position reduces its vertical extend to a range of approx. 80 m after the bottom current onset.*

l270: When you are discussing thermocline depth, it is probably worth it defining exactly what you mean. Is it the base of the thermocline, the top, the middle, a specific isotherm depth?

Thermocline is defined as the depth of greatest vertical temperature gradient. It has been added to the text. *In the following, the thermocline is defined as the greatest vertical temperature gradient.*

Fig. 10: Define the thermocline depth. Probably worth merging Fig. 10 and 11 to be able to compare easily timing between curves. Add also vertical grid to ease even more the comparison.

The thermocline depth has been calculated as the depth at which the greatest vertical temperature gradient can be found along the continental slope. We combined the two figures into one.

l287: What is the explanation for the presence of a V-shape after a regime shift or during intrusion of mCDW on the shelf. In the introduction, the presence of DSW cascading need critical in the formation of the V-shape. Once the mCDW flood the shelf, there is no more cascading. So I am surprised by the presence of a V shape in this case.

The V-shape is constrained to the upper ocean. At the depth of the inflow, no V-shape is formed. The V-shape in the upper ocean still follows the same principles as in the beginning of the simulation, however the effects are smaller and the mixing does not go as deep any more. An explanation has been added to the text (see main comments).

Section 4

Section 4.2

l344: Same question as for section 3.6 on the processes that drive the V shape without DSW cascading.

See above and main comment.

l355: please reformulate 'Ryan (2017) showed that during ... suppress the isopycnals ...' sentence. I don't really understand the first part. What is suppressing the isopycnals at the continental slope.

Maybe suppress is the wrong choice, subduct works better. The production of DSW and its export across the shelf break in winter entrain more overlying water masses. This reduces or stops the on-shore transport of mWDW. The text has ben changed accordingly.

l358: Please reformulate 'in shallower than sill depth'.

Done.

section 4.4

l378: add a description of the eddy param in model description.

A brief description of the model sub-scale parametrization has been added to the methods (see comment on lines l86-l96).

l382: You mentioned issue with the lack of eddy. Is it also true in your case with the eddy parametrisation ?

We haven't tested it, but it might hypothetically be possible that with the reduced eddy presence due to the lack of resolution, the model might underestimate cross-slope volume transport and the V-shape. It is possible but would need further testing.

Conclusion

l404: Please reformulate, I had to re-read it multiple time to understand it. I found some term vague like 'temporary disturbance'.

The sentence has been split for easier readability. *The criterion of spatial coherency of the V-shape along the continental slope, quantified by the grade of connectivity, is not usable as a tool to predict an imminent regime shift because the onshore transport of modified Warm Deep Water is, contrary to our expectations, not a result of a weakening of the slope front. Instead, the cross-slope transport leads to a temporary disturbance of the ASF and the associated V-shape. While the density minimum is completely restored after disruption in present-day climate, in a warming climate the distinct V-shape remains confined to the upper ocean.*