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Title: Subsurface Initiation of Deep Convection near Maud Rise

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Point-by-point reply to reviewer #3

September 24, 2020

We thank Ethan Campbell for his careful reading and for the very useful comments on the manuscript. We have divided the comments into six specific ones and answer those point by point with reference to figures at the bottom of the document.

Specific Comments:

1. *Repeat hydrographic surveys from 1984-2008 along the Greenwich Meridian, crossing Maud Rise, show no sign of marked heat accumulation following ventilation during the massive 1974-1976 Weddell polynyas (Fahrbach et al. 2011). The small warming trend observed is over one order of magnitude smaller than that examined in the authors' companion submission following polynya events (van Westen and Dijkstra, in review), and large decadal fluctuations complicate the detection of even that small observed trend. In fact, local rebound in heat content near Maud Rise following the major 1974-1976 polynyas occurred by 1984 at the latest (Smedsrud 2005), and likely in shorter time. Analysis of about 3,000 temperature profiles from 2002-2017 from ships, floats, and instrumented seals indicated that there was no local buildup of mid-depth heat leading to the 2016-2017 Maud Rise polynyas (Campbell et al. 2019; see section 'Sub-pycnocline temperature records' and Extended Data Fig. 9). These substantial differences between models and reality unfortunately limit the utility of the authors' CESM simulation as a direct analogue for investigating the recent polynya events.*

   Author's reply:
   We have examined the properties (e.g. temperature and salinity) of the Weddell Deep Water (WDW) along the Greenwich Meridian (Figure 1).

During Maud Rise Polynya (MRP) events, the WDW temperature decreases as heat is ventilated by vertical mixing. After the MRP event during model years 205 – 209, the WDW is relatively cold and the temperature increases over time. Prior to model year 231, the WDW temperature reaches maximum values which corresponds to the growing subsurface instabilities. In model year 231, an MRP forms and the WDW temperature decreases again. The build-up of the WDW heat reservoir has the same period of the multidecadal build-up of subsurface heat over Maud Rise.

Between polynya years (model years 210 – 230), we find a WDW temperature trend of 0.064 K per decade. Between model years 210 – 240, we find a trend of 0.024 K per decade. These trends are of the same order as in Smedsrud (2005). The peak-to-peak difference in the WDW temperature is ~ 0.1°C.

We also analysed the WDW using Mercator (1993 – 2018) along the Greenwich Meridian. We find that in Mercator, prior to the 2016 – 2017 MRP, the WDW is relatively warmer compared to the time mean (1993 – 2018). There is inter-annual variability of the WDW temperature after the appearance of small MRPs with a peak-to-peak difference of 0.05°, half of that compared to the CESM. The limited subsurface heat reservoir explains why subsurface convection ceases during 2016.

Changes in manuscript:
We will include an analysis of the WDW and compare these with observational records; both the CESM and Mercator results will be discussed here.

2. *In contrast, the published high-resolution model simulations that best reproduce the Maud Rise polynya phenomenon point to upper-ocean destratification from surface salinity anomalies, not subsurface heat accumulation, as most important in triggering polynyas (Kurtakoti et al. 2018; Kaufman et al. 2020). These papers should be cited and discussed. Along similar lines, the authors neglect the observational and theoretical evidence that points to low upper-ocean haline stratification as a critical factor in allowing Maud Rise polynyas to emerge in 2016 and 2017 but not in most other years (Campbell et al. 2019). It is inaccurate to characterize our study as attributing the 2016 polynya solely to intense winter storms (as stated in the authors' Abstract,*

Lines 1-2; Page 8, Lines 21-23; Page 12, Lines 11-12). Both weak upper-ocean stratification and strong storms appear to have been necessary, and strong storms which were more frequent than usual in 2016 but are still a regular occurrence in most (non-polynya) years ? are apparently not a sufficient condition for polynya formation. While the authors attribute the 2017 polynya to a 'weakly stable surface layer' (e.g., Abstract, Line 7), they look elsewhere for the immediate cause of the earlier 2016 polynya. I find this puzzling, as the profiling float measurements examined in Campbell et al. (2019) show that a 'weakly stable surface layer' existed both prior to the 2016 polynya as well as during the following winter.

Author's reply:
We agree with the reviewer that the surface layer was indeed weakly stratified in 2016. We have investigated in more detail the surface salinity anomalies in the CESM (Figure 2). Salt from Ekman upwelling (following Campbell et al. (2019)) shows that more salt is entrained during sea-ice free months (January – May) compared to the time mean (anomaly of 0.039 Psu in model year 231). The depth-averaged salinity over the mixed layer depth was also more saline in model year 231 and the magnitude of these anomalies are comparable, but slightly weaker, compared to Kurtakoti et al. (2018).

To examine the effect of surface driven convection by these salt anomalies, we have re-run the CESM and written out the daily-averaged vertical diffusivities for model year 231 (Figure 3c). The vertical diffusivity can be used to examine vertical mixing in the CESM, as is done in Dufour et al. (2017). We find that the mixed layer displays some vertical mixing, however, the magnitude is a factor 3 smaller compared to the subsurface mixing prior to MRP formation (Figure 3d). Surface salinity anomalies can contribute to preconditioning of the Maud Rise region, but are too weak to induce deep convection.

Changes in manuscript:
We will include an analysis of the surface salinity anomalies and the vertical diffusivities in the revised paper. These results will be compared to observations and other model studies.

3. *Surface-driven deep convection is a phenomenon that has been well-documented in decades of observations from the North Atlantic and*

Mediterranean Sea (e.g., de Jong et al. 2012; Testor et al. 2018). Its theoretical underpinnings are also reasonably well-understood (e.g., Marshall and Schott 1999). In my view, there is little reason to expect that deep convection in the Weddell Sea is not similarly initiated by buoyancy loss and/or dynamic perturbations in the upper ocean. Indeed, this is the canonical model for the formation of polynyas near Maud Rise (Martinson et al. 1981; Motoi et al. 1987). However, if the authors wish to assert that subsurface-initiated deep convection is of real importance, I would suggest critically engaging with literature that may offer a theoretical basis for this mechanism. Harcourt (2005) and Akitomo (2019), for instance, describe subtle processes by which subsurface overturning may be initiated through nonlinearities in the seawater equation of state, but it is important to recognise that this is a fundamentally different sequence of events than that which seems to be occurring in the authors' CESM run.

Author's reply:
There are three different types of oceanic convection (Akitoma 1999, Su et al. 2016): convection by buoyancy loss (type I convection), thermobaric convection (type II convection) and thermobaric cabbeling (type III convection). A nonlinear equation of state is essential only for the latter two types. We are dealing here with just type I convection.

Near Maud Rise, surface buoyancy loss occurs at the surface when the surface is strongly cooled during Austral winter time and by the contribution of sea-ice formation (e.g. brine rejection). In the CESM, the mixed layer depth is seasonally varying prior to MRP formation (Figure 4). The build-up of a subsurface heat reservoir (Figure 1) induces buoyancy gain by thermal expansion. Parcels located at subsurface depths experience an upward force and mix with the layers above.

To study the subsurface mixing, we have written out the daily-averaged vertical diffusivities (Figure 3c) from the CESM simulation. The subsurface vertical diffusivities are increasing indicating that the water column overturns at subsurface depths. There is no increase in the surface vertical diffusivities prior to MRP formation (Figure 3d).

Changes in manuscript:
We will include a better description of the subsurface convection and

the analysis of the vertical diffusivities in the revised manuscript.

4. *Regardless of the theoretical feasibility of subsurface-initiated overturning, the phenomenon that the authors highlight from their CESM run is unlikely to have occurred in 2016. In the attached Figure 1 (see below), I have plotted potential density profiles from the Argo float 5904471, which was present at Maud Rise during the recent polynyas (Campbell et al. 2019). This figure is a direct comparison to the authors' Figure 2c from their CESM run, which shows a statically unstable profile below about 75 m prior to polynya formation. In contrast, the observations show that potential density increased steadily with depth, including immediately prior to the 2016 polynya, as is typical throughout the world ocean. While the CESM profile seems to be characterized by a bolus of mid-depth heat anomalies, which create a remarkably thick potential density inversion layer, these features are unsurprisingly absent in the observations. (This is to say nothing of the model's twofold bias in its deep-to-surface potential density difference, which is greater than 0.2 kg/m3 in the model but is no more than 0.1 kg/m3 in the observations, or the inappropriate use of surface-referenced potential density [sigma-theta] to characterize inversions when a locally-referenced potential density should be used instead.)*

   Author's reply:
   As stated in the manuscript, subsurface static instabilities are (very) localised in the CESM. The static instabilities are found below the regions where the sea ice opens in August for both CESM and Mercator. The Argo float was located outside these static unstable regions and, as expected, the water column is statically stable as shown by the reviewer. This float can therefore not reject our hypothesis and to our knowledge, there are no direct measurements of the water column directly below the region of a developing MRP. To analyse the water column directly below the polynya, we make use of the Mercator. Of course, Mercator also parametrises different processes but the background density profile is comparable to that of the Argo float.

   We have analysed the vertical diffusivity in the CESM and these are linked to the growing subsurface static instabilities. These subsurface static instabilities are connected to relatively high temperatures of the WDW. The Mercator diffusivities are not available, but static instabilities are also found below the region of relatively low sea-ice concentrations over Maud Rise.

Changes in manuscript:
Based on this comment, we will discuss the Argo float results in more detail.

5. *The authors seem to dismiss the possibility of using the float observations to conduct an analysis similar to their assessment of CESM model output and Mercator reanalysis data, stating that 'these Argo float observations are too sparse (every 10 days) to analyse the oceanic state (and e.g. convection)' (Page 9, Lines 28-30). In the context of investigating preconditioning for a polynya, this is inaccurate. The oceanic state – particularly below the mixed layer – does not vary substantially on time scales less than 10 days, as seems to be indicated by the authors' own analysis of the CESM output and Mercator data. The float data are plenty useful and are, in fact, the best records we have on conditions in 2016 and 2017 at Maud Rise. (It is important to note here that the Mercator reanalysis data is poorly constrained in the ice-covered Weddell Sea, and should be approached with greater caution than is done here. Comparison with a single float profile (Figure 4b) towards which the reanalysis is likely nudged – is not an adequate validation of its skill.*

   Author's reply:
   In case of convection, the oceanic state can vary on short time scales less than 10 days. Besides, the Argo float was not located inside the region of static instabilities, as discussed in Comment 4. As stated in the manuscript (page 11, lines 10 – 13), we determined the subsurface convection using the Argo float. We find that between 110 – 240 m depths, the water column is statically unstable in the Argo profile. Mercator displays a well-mixed layer between these depths, indicating that the water column has likely overturned at these depths. Note that the Argo float measures at a particular time and the Mercator consists of daily-averaged fields. Although the Argo floats are near Maud Rise, they didn't measure the water column directly below an MRP.

   We agree with the reviewer that the Mercator reanalysis products also has its shortcomings, but still reasonable agrees with Argo float and SSMR-SSM/I measurements. The Mercator indicates several interesting results which can not be captured by the Argo float. For example, the decreased vertical extent of subsurface convection (red curve in Figure 4d) which is a plausible explanation why the MRP closes in 2016. There is no deepening of the mixed layer depth, which is important in the case of surface-driven convection.

Changes in manuscript:
We will stress that the Argo floats are not located in the regions of subsurface static instabilities and that there are no other direct observations of the initiation of (sub)surface convection. This also motivates the use of other products such as Mercator in this study.

6. *Ultimately, the float observations analyzed in Campbell et al. (2019) as well as the body of previous work on Weddell Sea polynyas and hydrography offer ample evidence that model-observation disagreement is severe in this region and in the context of this phenomenon. With this in mind, I would argue that it is probably counterproductive to interrogate the causes of observed polynya events through direct comparison with a model that behaves very differently than the real world.*

   Author's reply:
   We agree with the author that also the CESM has its shortcomings, but we do not think the model-data mismatch disqualifies the model for analysing the formation mechanism of MRP events. Note that also the study in Kurtakoti et al. (2018), which the reviewer appears to find credible, is done with only a slightly different CESM configuration.

   Changes in manuscript:
   A discussion on whether the model is fit for purpose, based on a comparison with available observations, will be included in the revised paper.

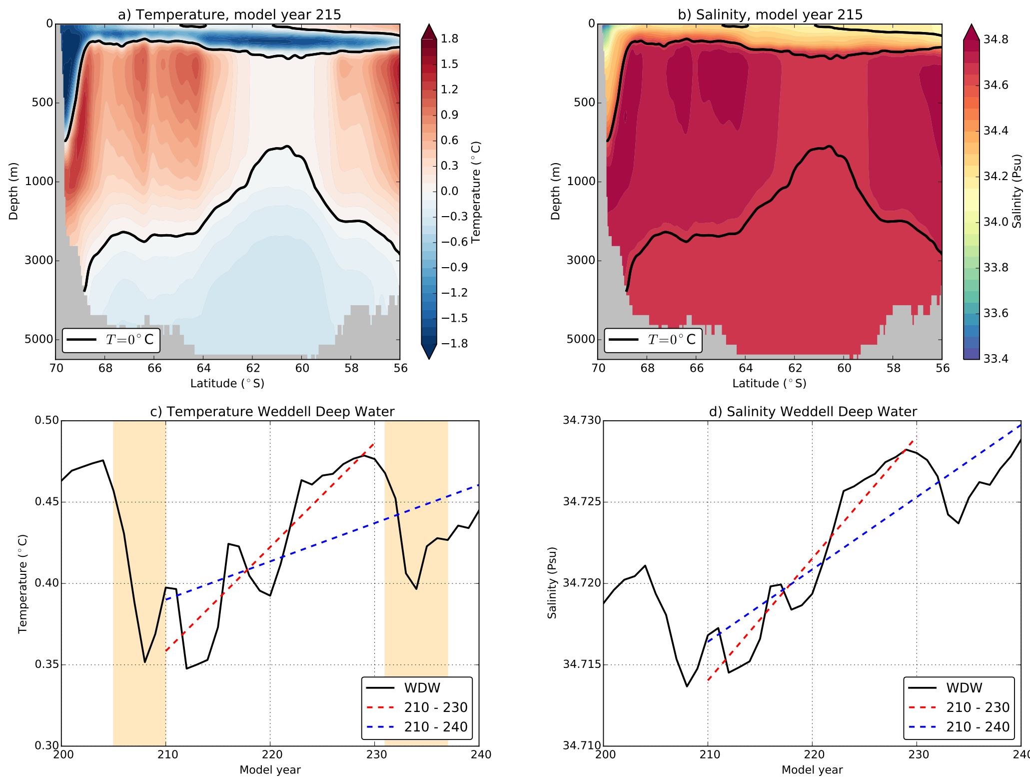

Figure 1: (a & b): Zonal mean (1°W – 1°E) of temperature and salinity along the Greenwich Meridian. The displayed values are yearly averages for model year 215. The black contour displays the 0°C, which marks the WDW. (c & d): Time evolution of the temperature and salinity of the WDW. The dashed lines are linear trends between model years 210 – 230 (red) and model years 210 – 240 (blue). The shading indicates the polynya years.

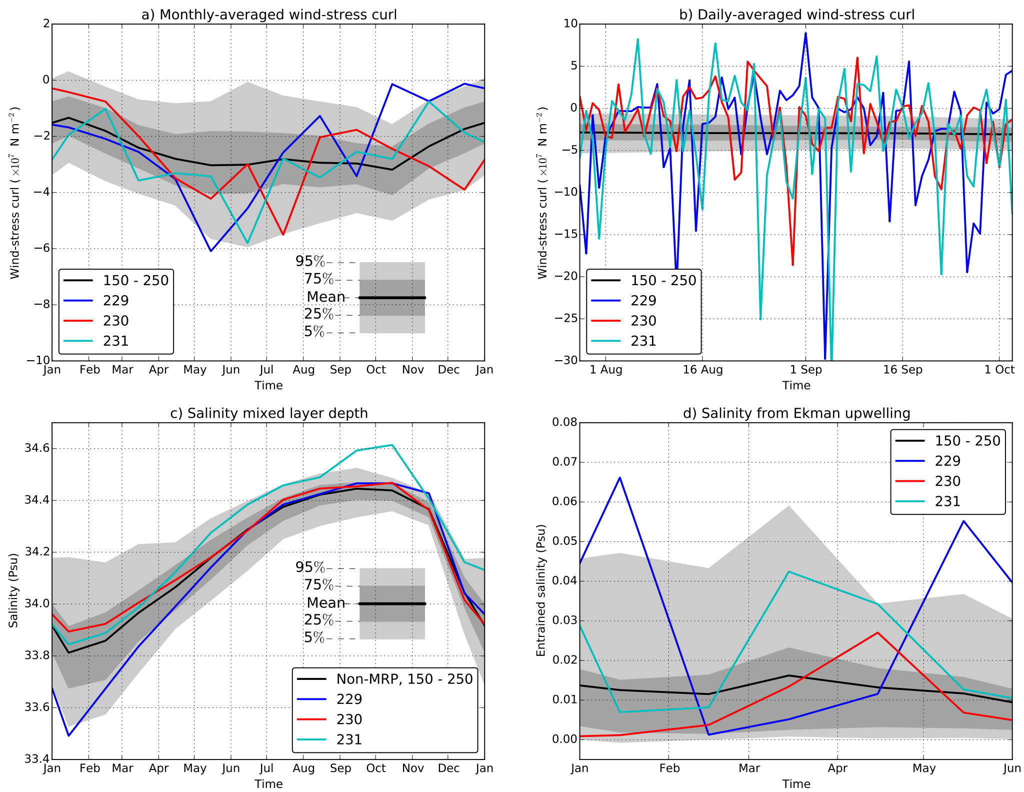

Figure 2: (a): Monthly-averaged magnitude of the wind-stress curl over the Polynya region for model years 229, 230 and 231. The shading indicates the climate variability, where the dark (light) shading correspond to the 25% – 75% (5% – 95%) percentile levels, the black curve is the climatology mean (model years 150 – 250). (b): Same as a), but now for daily averages. The shading is the same as in a). (c): Depth-averaged salinity over the mixed layer depth for model years 229, 230 and 231. The shading indicates the climate variability of this quantity (same as a)), but now only the non-MRP years are considered in the climatology. (d): The entrained salinity into the mixed layer from Ekman dynamics for model year 229, 230 and 231. The shading indicates the climate variability of this quantity (same as a)).

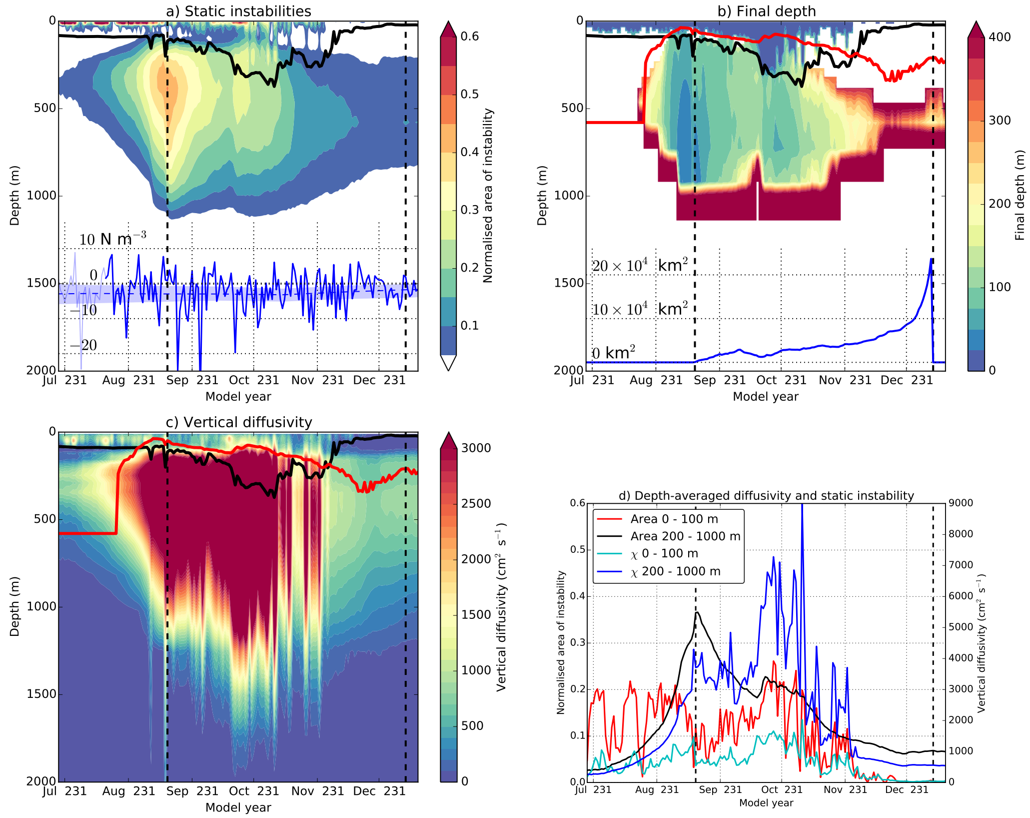

Figure 3: (a): Area per depth level where the water column in the Polynya region is statically unstable ($\mathcal{S} > 0$), normalised to the total area at that depth level. The blue curve is the daily-averaged magnitude of the wind-stress curl over the Polynya region, same as in Figure 2b. (b): Final depth of fluid elements due to (subsurface) convection. Only regions where deviations from the initial depth occur are displayed. The red curve shows the final depth of convection initially starting at $z_{ref} = 580$ m. The blue curve (bottom part) is the total area of the model year 231 MRP. (c): The vertical diffusivity (χ) for temperature, spatially averaged over the Polynya region. The red curve is the same as in b). In a) – c), the black curve shows the maximum mixed layer depth spatially averaged over the Polynya region. (d): The depth-averaged vertical diffusivity (χ) and normalised area of static instabilities over the upper 100 m and between 200 – 1000 m. In all figures, the dashed lines indicate the formation (20 August) and ending (14 December) of the MRP.

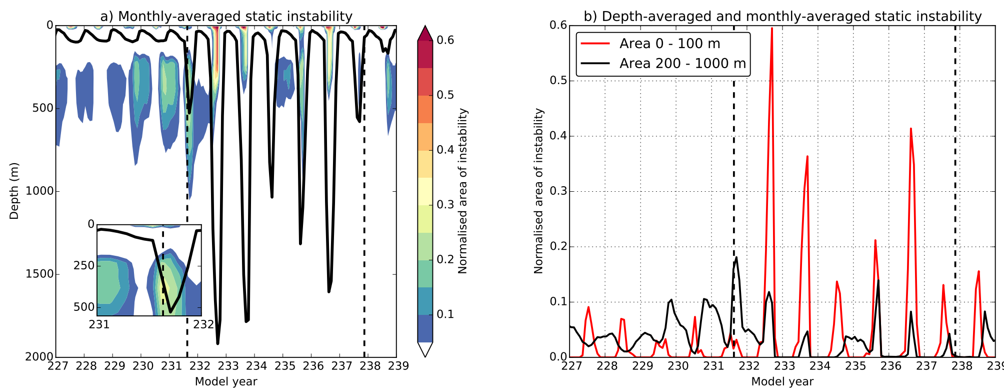

Figure 4: (a): Area per depth level where the water column in the Polynya region is statically unstable ($\mathcal{S} > 0$), normalised to the total area at that depth level. (b): The depth-averaged normalised area of static instabilities over the upper 100 m and between 200 – 1000 m. In both figures, the dashed lines indicate the beginning (model year 231) and ending (model year 237) of the multiyear MRPs. The model output analysed consists of monthly averages.