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Interactive comment on "Dynamics of Large Pelagic Ice Crystals in an Antarctic Ice Shelf Water Plume Flowing Beneath Land-Fast Sea Ice" *by* Craig Stevens et al.

Craig Stevens et al.

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Author: We thank the Reviewer for the time and effort in commenting on our manuscript and especially for their constructive suggestions and we respond to these as best we can below. We (i) modified the title, (ii) improved the clarity of the Abstract and Introduction, (iii) removed a theme on the role of sediment and (iv) clarified when various data were collected. In addition, we modified several of the Figures in response to their points. We believe this has resulted in significant improvements in the manuscript and the "rare dataset" it presents.

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Discussion paper

Rev2: General Comments: ISW circulation processes and the deposition of frazil/platelet ice crystals at the interface between the ocean and SIPL are not well observed and thus not well understood. The processes influencing and forming the SIPL are thus very difficult to constrain. This paper presents important observations/analysis of coincident ocean properties, currents, boundary-layer processes and frazil/platelet ice beneath land-fast sea ice in a region of significant supercooled ISW outflow in McMurdo Sound. This is a rare dataset that provides much-needed information about the processes at play beneath the SIPL. However, I have several major comments that should be addressed before this paper is accepted to 'The Cryosphere'.

Au: We are pleased they found it "a rare dataset that provides much-needed information about the processes at play beneath the SIPL". There remains much to be discovered in the under-sampled Antarctic oceanic environment. It is noteworthy that the recent paper in TC by Cheng et al 2019 that the Reviewer brought to our attention closes with a call for more observations of exactly the kind we present.

Rev2: 1) My main comment is that the research question is not clearly set up in the introduction and nor is it explicit in the abstract. This is a consistent thread throughout the paper and I had to read it several times before I could extract what this research aimed to address and why; why these specific measurements were made; and what their relevance was in the context of the research question and the greater motivation of the study. The authors could address this by better framing and providing clarity on the motivations underpinning the research objectives. Additionally, spelling out why these specific measurements were made (especially for the non-expert in physical oceanography), what information they provide, and the significance and relevance of that information.

Au: Reviewer 1 made a similar comment and we have made efforts to improve this aspect. It is challenging for small-scale process studies to connect to the global system while retaining focus on the smaller scales. We are fortunate that the major review by Hoppmann et al has just come out providing excellent context. We have added some motivational text right at the start. It now says *"Here we examine the dynamics of large floating crystals observed to be suspended in the boundary-layer beneath a fast ice layer near a large Antarctic ice shelf cavity. This is unusual as one would expect the crystals to either be much smaller or rapidly float to merge into the under-ice aggregation of ice crystals. The existence and persistence of such large crystals must influence regional variability in Antarctic sea ice."*

Rev2: It would be useful to highlight the rarity of the observations and the importance of frazil/platelet ice size distributions/concentrations for understanding ISW plume dynamics and for informing relevant models such as described in Hughes et al. 2014 and Cheng et al. 2019.

Au: This is a good point and we have added the following… *"Is there evidence of large suspended crystals? While they are known to exist on the ice underside there is little evidence confirming their presence in the water column itself. If they can be identified this would be a novel contribution and aid future model development."*

Rev2: 2) I find the 'Dirty Ice' sedimentation hypothesis contradictory. In the introduction, the authors state that sediment in the ice is partly marine in origin, and likely entrained in marine ice as it formed on the underside of the ice shelf and that this is evidence of significant ISW outflow from this part of the McMurdo Ice Shelf. They then suggest that the sediment is providing seed material for frazil ice nucleation and could be a factor in the SIPL distribution beneath the land-fast sea ice in McMurdo Sound. My understanding is that previous oceanographic, sea ice core and SIPL measurements have shown that the SIPL distribution is driven by significant ISW outflow in this part of the sound. More to the point, there are no observations or any analysis of suspended sediment load/particulates or frazil ice nucleation in this study and though an interesting discussion, section 4.3 seems superfluous and not directly relevant to this work. I recommend that this section is removed or supported with evidence.

Au: The point is that the situation needs both sediment as a nucleator AND the ISW to drive the freezing. However, in keeping with both Reviewers advice we have removed the sediment theme, modified the closing schematic and deleted or shifted the associated text.

Rev2: 3) My final comment is that the paper should include a conclusion section providing a clear summary of the background context and motivation for the study, what was done and why, the main results and the significance and relevance of the findings. I struggled to extract the main findings of this work.

Au: We had incorporated closure into the final paragraph but now have inserted a subheading title and more clearly reiterated the main points.

Specific Comments: (L refers to Line numbers)

Rev2: Title: I suggest changing ‘large pelagic’ to platelet ice crystals

Au: Rev 1 was confused by the pelagic term so we will replace this. However, as noted by the recent Hoppmann review “platelet” itself generates confusion so we will use “large suspended crystals”. The revised title now says... *”Dynamics of Large Suspended Ice Crystals in an Antarctic Ice Shelf Water Plume Flowing Beneath Land-Fast Sea Ice”*.

Rev2: L 10-11: Could you state why were these observations are presented and when they were collected?

Au: The text now says... *” The connections between ice shelf cavities and sea ice influence sea ice development and persistence. One unique feature is the potential for sea ice growth due to crystal accretion. Here we present unique observations of boundary-layer processes and ice crystal behaviour in an Ice Shelf Water outflow region from the Ross/McMurdo Ice Shelves. From a fast ice field camp during the Spring* *of 2015, we captured the kinematics of free-floating relatively large (many 10s of mm in scale) ice crystals that were advecting and then settling upwards in a depositional layer on the sea ice underside (SIPL, sub-ice platelet layer)."*

Rev2: L 23: I suggest changing 'fully grown" to larger platelet ice crystals of ? cm dimension.

Au: The text has been modified to say... *"This second class of backscatter was associated with crystal sizes far larger than typical, certainly larger than anything normally described as frazil. Measurement indicated crystal width scales of the range 5-200 mm with an average of 93-101 mm depending on the year."*

Rev2: L 23: What dimension are you referring to by 'Crystal scales'?

Au: Crystal "width" as per above text. Note we enhance this aspect later on with an improved figure that now shows the distribution of the major and minor crystal dimensions.

Rev2: L 31-32: I suggest changing to 'a potential driver contributing to: : :'.

Au: OK change made

Rev2: L 33-34: This sentence needs more detailed information.

Au: We were trying to constrain the Introduction to the boundary-layer processes at hand rather than a wide range of polar oceanographic processes. *"The meltwater exiting the cavity is typically very cold as it comprises water formed within the cavity at depth so that the local freezing point temperature is depressed due to the pressure. This water mixes with the ambient ocean resulting in a fresher, cold seawater plume that seeks out the fastest upward flow path on the shelf underside subject to the Coriolis* *force and basal slope (MacAyeal 1985; Jenkins and Bombusch 1995; Smedsrud and Jenkins 2005; Stevens et al., 2020).”*

Rev2: L 37: Sustained melting and/or decay of what? This sentence needs a reference.

Au: The sentence has been reworked and references added. It now says *“These plumes will develop depending on the balance of inflow, re-freezing either of the sea ice underside or in the formation of suspended crystals removing their thermal deficit, and mixing with warmer waters.”*

Rev2: L 41-42: I do not fully understand this statement. Can you develop?

Au: We merged it with the bracketing sentences so the section now says... *“At this point the basal slope driver of flow ceases and the persistence of the supercool plume is controlled by initial buoyancy, growth of new ice, topography and mixing (Hughes et al., 2014) which are all changing relatively rapidly. This plume of supercool water influences sea ice growth by both enhancing upper ocean stratification and absorbing heat (Robinson et al., 2014; McPhee et al., 2016). Whether or not there is an associated phase change is critical and so the presence of ice crystals within the upper water column has a number of implications from thermal budgets, convection and ecological habitat (Hoppmann et al., 2020).”*

Rev2: L 46-56: I suggest including the work of Cheng et al. 2019 and emphasising the importance of suspended ice crystal load for ISW plume dynamics and for understanding the processes that influence the SIPL.

Au: This is a good point thanks – we were not aware of the reference and had included a number of other older references. We now include this reference and note the point that it advocates for more observations of the processes described here.

Rev2: L 65: I suggest changing camps to observations.

Au: OK but observations doesn't quite serve the purpose as it is meant to identify a sequence of "experiments". We have amended to. . . "long sequence of sea ice camps in the McMurdo Sound region (Robinson et al., 2020) enabled observations that have revealed. . ."

Rev2: L 67: Hunkeler et al. 2015 and Hoppman et al. 2020 are not specific to SIPL studies in McMurdo Sound.

Au: OK - we were seeking to generalise but can split this to now have sentences on the local situation and also the wider Antarctic evidence.

Rev2: L 75-85: This paragraph should be developed to set up the research question better and to describe what was done and why.

Au: We have reworked this paragraph and the end of the previous paragraph to meet the Reviewer's point. The text now says. . . *"Here we examine the dynamics of large ice crystals observed freely floating in the upper ocean and the turbulence within which they move in the context of background hydrographic conditions. Hoppmann et al. (2020) review our present understanding of Antarctic platelet ice and makes it clear the topic is still in a discovery phase – partly due to the challenges of making comprehensive observations. At the same time, modelling approaches have needed to advance – creating a tension in that not all the relevant processes and scales are known. Geophysical boundary-layers are well understood and it is known that ice crystals on the sea ice underside influences interfacial momentum transfer, sea ice composition and strength as well as ecological habitat throughout localised parts of Antarctic coastal waters. However, if these crystals can accumulate initially as large crystals rather than primarily grown once settled will make a difference to these processes. Consequently, the presence of large suspended crystals result in a number of questions that provide focal points for the present study. (1) Is there evidence of large suspended crystals?*

While they are known to exist on the ice underside there is little prior published evidence confirming their presence in the water column itself. This observation is novel and provides a guide for future model development. (2) Is there a relationship between crystal behaviour and the turbulent under-ice boundary-layer structure? In particular it is useful to assess the role turbulence plays in suspending the crystals. (3) Finally, considering in broad terms what the large-scale implications of such finescale mechanics might be provides a way of contextualising the wider effect the observed conditions could have."

Rev2: L 89: 'over an ocean depth'

Au: change made

Rev2: L 103: Frazer et al. 2020 is in review.

Au: This is now published and the reference is amended - Frazer E.K., Langhorne P.J., Leonard G.H., Robinson N.J., Schumayer D.: Observations of the size distribution of frazil ice in an Ice Shelf Water plume, Geophys. Res. Lett., p.e2020GL090498 doi.org/10.1029/2020GL090498 2020.

Rev2: L 107: I suggest providing the dimensions of the ice hole.

Au: *"1 m x 1 m x 2.3 m blocks of sea ice"* now added

Rev2: L 110-111: Does this statement refer to platelet ice and frazil ice crystals? This needs clarification.

Au: The sentence specifically addresses where the crystal types fit within a size continuum. It now says "Hoppmann et al. (2020) describes the semantics of platelets and frazil. For present purposes we consider them to be ends of a spectrum of the same physical crystal evolutionary process."

Rev2: L115: Is there any previous evidence that it is a tightly interlocked matrix?

Au: Robinson et al. 2014 addresses this and they say... *Loose accumulations of buoyant platelet ice crystals beneath sea ice in McMurdo Sound have previously been termed "subice platelet layers" [Paige, 1966; Gow et al., 1998; Crocker and Wadhams, 1989; Jones and Hill, 2001; Mahoney et al., 2011; Gough et al., 2012]. However, that term does not adequately describe the network of unconsolidated platelets observed in the present study in which individual crystals grew through each other after floating to the surface to create a delicate lattice. Hence, we use the term "subice platelet matrix" to describe a thick, porous, and semirigid framework that is bathed in a continuous supply of supercooled water sourced from under an ice shelf.* The key word is "semirigid". We now include these references.

Rev2: L127-131: Where is the echosounder pointing? Upward to the SIPL base? Is the beam 3 m wide at 25 m depth or at the SIPL base? It would be very useful to have an estimation of the field of view.

Au: Good point as the original text was ambiguous. The transducer is facing downward and located right at the base of the SIPL. The text now says... *"We placed a downward-looking Simrad EK60 200 kHz echo sounder right at the base of the SIPL recording acoustic backscatter at 1 Hz with 4 cm vertical resolution over a sampling cone that is 7 degrees across, so that at a depth of 25 m the cone is three m wide. The cone has side-lobes in the upper 5 m of the water column that are as wide as 30 deg. The beam-width is not particularly critical so long as it is wide-enough that scatterers register some rise component (vertical resolution). With horizontal flows of around 0.05 m s-1 this means that a reflector would stay in the beam for a maximum of nearly two minutes at 5 m with a 30-degree cone. Useful backscatter was consistently detected as deep as 30 m."*

Rev2: L139: What is meant by superficial appearances? Can you develop and better clarify this statement?

Au: We meant that if one quickly looked at the figure one might infer a horizontal dimension to the data that does not exist. We have re-worded. *"The angled trajectories relate to the crystal rise speed and are unconnected to the tidal advection. Horizontal flow controls the persistence of individual reflectors as it is responsible for moving crystals in and out of the acoustic beam."*

Rev2: L143-154: When were these measurements carried out and at what point on the tidal cycle?

Au: A number of CTD profiles were recorded but only one is used here. The timing of this is now described in Section 3.1.

Rev2: L 165-172: Again, when were these measurements carried out and at what point on the tidal cycle?

Au: As per above this has now been included in the text.

Rev2: L 175-176: What indications are there that this be the result of buoyantly forced ISW plume?

Au: We have moderated the claim and included some text and a reference. *"This is possibly the result of the buoyantly forced ice shelf water plume which is a consistent feature in the region (Robinson et al. 2014; Hughes et al. 2014) which, due to buoyancy, preferentially flows on the ice underside."*

Rev2: L 176-178: At what point on the tidal cycle were speeds of 0.1 m/s observed and in what direction? Please see comments provided below on Figure 3. It would be useful to provide date and month in parentheses after Julian Day.

Au: This is a good point to pick up on and there's a whole aspect of spring-vs-neap mixing and the relationship to buoyancy induced currents. However, that is a different focus than the crystal rise vs turbulence aspect here. The neap phase has a strong non-tidal northward bias whereas moving into the spring tides it becomes more bi-directional. This "paradox" is common in estuarine conditions. We now add some text in the new section 4.3 where we connect what we have observed at the local scale to the wider system. It says.... *"The timescale for this transport is of the order of a month. These data make it clear that the variation in tides over this period will influence the crystal sedimentation budget. First, the data indicate that the buoyancy driven upper ocean residual flow is faster and more continual during neap tides (Figure 3). So paradoxically, the low flow conditions are only seen away from neap conditions. The lowering of the flow speed and hence boundary layer turbulence if a shift to higher turbulent Péclet number conditions (Figure 11) so that buoyancy dominates. Consequently, the critical phase for the SIPL is slack water during spring tides which will allow crystals to settle out. The implication then is that the critical property to assess is the timescale over which a newly settled crystal becomes locked into the SIPL."*

Rev2: L 180: I found the away and toward ice shelf convention confusing in the text and very difficult to interpret in Figure 3.

Au: We are not sure what more we can do here as the directions are in a "towards True North" angular convention and the ice shelves are to the south. We could put figure 3a b in terms of U and V components but we would still need to include a speed trace as this is the driver of the boundary-layer turbulence. We believe the additional text requested elsewhere by this Reviewer will emphasize why it is useful to have the speed.

Rev2: L 183: Is there a characteristic shape of platelet ice crystals?

Au: Good question – clearly they are flat and disk like. We have added in the distribution of minimum to maximum crystal dimensions to Fig. 4 showing the average ratio to be 0.67.

Rev2: L213-226: Can you be more specific about flow direction, point on the tidal cycle, temperature/salinity/backscatter changes and provide a date/time for each DOY.

Au: We originally included the arrows to highlight unambiguously the points we were discussing so the reader had absolute clarity about what we were talking about. Presumably the Reviewer is asking for these points to be carried over more directly into the text? We have amended the text slightly to carry across these points more clearly. *"For most of the observation period the vertically integrated acoustic backscatter time-series does not show any obvious consistent correlation with the velocity and scalar properties. However, exceptions occur near the end of day 298 (peak 2 in Figure 3) at which point we see shift from uni-directional flow through to a tidal oscillation and this comes at the end of a period of dropping temperatures (although only dropping by 30 mK) and increasing salinity. Simultaneously we observed the rise period to the highest backscatter (which is log-scale db). There is another instance where speed peaks correspond to changes in temperature, salinity and backscatter (peak 5). Near the end of the experiment at peak 7 again a velocity peak coincided with a change in backscatter, flow direction and salinity suggesting an entirely new water mass was moving by. It is noteworthy that the 3-4-day trends are comparable between temperature and acoustic backscatter as the pre day 299 conditions give way to a decline in backscatter while temperatures rise steadily over days 299-302. After day 302 the trends in both temperature and backscatter remain flat. These periods also correspond to changes in the tidal structure with unidirectional flow prior to day 298 then transitioning (days 299-302) to steady back and forth tides (post day 301)."*

Rev2: L 230: What is the relevance of the frequency structure?

Au: We were not sure if this was a rhetorical question? Considering turbulence through a frequency perspective is useful as it permits insight into the energy-baring scales and the turbulent cascade. This is especially true in a boundary layer where there might be topographic effects, convection vs shear etc. Being able to do this with the acoustics, velocity and scalar properties is really insightful. We have added an explanatory sentence and augmented the closing of the paragraph. *"Examination of the frequency structure of the forcing flow and responding timeseries (backscatter and temperature) provides clues as to the nature of the mechanics (Figure 8). The current meter energy spectrum is constrained to lower frequencies (n.b. the timeseries are not long enough to enable analysis to extend much lower than the diurnal frequency) with much of the spectrum above 50 cpd reaching an apparent noise-floor implying that the variations seen in temperature and backscatter are not advection-driven."*

Rev2: L 242: What is meant by 2-5 m undulation in SIPL underside? Where, when and how was this observed?

Au: This was observed throughout the experiment and we have now included a new figure panel (Fig 5b). We don't believe this evolved over the period of our experiment but being certain of this is future work.

Rev2: L 251: I suggest using profiles instead of realisations.

Au: Agreed and change made.

Rev2: L293: I suggest rewording the last sentence of this paragraph.

Au: This is a reasonable suggestion and the text now says... *"The present situation is downstream of the Ross Ice Shelf cavity within which residence times in zero light likely to be in the range of 1-5 years (Reddy et al., 2010; Stevens et al., 2020) which further supports the suggestion that the targets and continuum are ice related rather than suspended biological organisms or sediment."*

Rev2: L307-308: The Hoppmann et al. 2015 and Hunkeler et al. 2015 studies were not carried out in McMurdo Sound.

Au: Agreed, we did not mean to imply this but can see the references were poorly placed. We have removed the "at this location".

Rev2: L 380-405 and L 417-420: As above in the specific comments about the cooccurrence of the 'Dirty Ice' and SIPL distribution.

Au: AS per above we have removed the original subsection 4.3 and deleted or shifted the associated text.

Rev2: L424: Richter et al. 2020 is in review.

Au: We await an update on the Richter manuscript. We have replaced it with a reference by Colleoni et al. 2018.

Rev2: L424-432: This paragraph could be developed further to provide a more substantiated context and broader outlook for this study.

Au: Agreed. We have reworked and expanded this text. It now includes points relating to modelling scales as well as the interaction between tides, polynya and sea ice formation. *"Modelling studies focusing at the regional ISW plume scale require more observational data and context (Chen et al. 2019). Colleoni et al. (2018) show that ice shelf-sea ice-ocean connections remain a major outstanding challenge in models operating at climate timescales. Incorporation of the processes described here into modelling that typically resolve scales around 2 km or greater will be a challenge. A starting point might be the role present large platelets play in the McMurdo Sound polynya formation (Dai et al., 2020). Water column evolution and sea ice formation in polynya are spatially constrained phenomena driven by short, high-energy wind events that then drive formation of new sea ice. This energy conversion will be influenced* *by the presence of ISW that will enhance the processes. It is the by-product of this sequence that generates high salinity shelf water that ultimately has a global thermohaline impact. As large-scale models seek to improve their representation of polynya that will need to better account for the nature of ice shelf water plumes. Similarly, the present data suggest that such large spatiotemporal representations will need to find ways of including the effects of tidal fluctuations in some integrated fashion.*

The topic is clearly still in a discovery phase with many fundamental questions remaining unanswered. This work suggests research themes for understanding sea ice formation near ice shelves should focus on the role of convection driven by SIPL crystal growth in modifying the turbulence in the upper water column and the feedbacks to the turbulence. In addition, the possible links between availability of nucleating material, crystal production and fate need to be examined, especially as to how this might support the formation of large, suspended ice crystals in an upper ocean influenced by tidal variations at both diurnal and spring-neap timescales."

Rev2: L 427: I do not understand this statement.

Au: Fair comment. As part of the response to the previous point we have re-worked the text to clarify the role these local-scale observations can play at the larger scale.

Technical Comments:

Rev2: 1) The Frazer et al. 2020 and Richter et al. 2020 studies are currently in review.

Au: The Frazer study has been published and we await an update on the Richter manuscript. We have replaced it with a reference by Colleoni et al. 2018.

Specific Comments on Figures

Rev2: Figure 1: I suggest combining a and c into one figure and masking out the land. A MODIS optical image showing the land-fast sea ice conditions at the time of the field campaign would be more informative as would stating the date/month of acquisition.

Au: We have developed a combined version of the figure. We left some aspects out to make it not too busy.

Rev2: Figure 2: At what point on the tidal cycle was this profile taken? And what are the DOY to relate to Figure 3?

Au: This has been amended and now says "This profile was from 0100 UTC on the 27th of October 2015 (DOY 300)". The associated text now says... "This example was recorded on DOY 300 as the tides moved into spring conditions and shows the upper layer..."

Rev2: Figure 3: I suggest moving a, b, c and d labels to top LH corner and put in parentheses; to make y-axis of tidal height larger. How was tidal height modelled? Please clarify convention for directions in a and b.

Au: The tidal amplitude is there to provide a spring/neap guide. We expand the tidal trace and moved the labels. Panel a is speed and has no direction and the panel b is direction towards True North as identified in the axis label and caption. Reference to the tidal height model is now included.

Rev2: Figure 6: State DOY to relate to Figure 3.

Au: The caption has been amended to now say... The segments come from (a) 25oct2015 at 1528 UTC (DOY 298.65), (b) 26oct2015 UTC at 0509 (DOY 299.84) and (c) 1nov2015 0438 UTC (DOY=305.19).

Rev2: Figure 12: Modify to account for changes to section 4.3 etc.

Au: Modified as requested... removed the wind-blown sediment, added in an arrow from the Ross cavity and modified the caption.

Rev2: Suggested reference: Cheng, C., Jenkins, A., Holland, P. R., Wang, Z., Liu, C., and Xia, R.: Responses of sub-ice platelet layer thickening rate and frazil-ice concentration to variations in ice-shelf water supercooling in McMurdo Sound, Antarctica, The Cryosphere, 13, 265–280, https://doi.org/10.5194/tc-13-265-2019 , 2019.

Au: added with thanks and linked to and quoted in several places through the revised text.

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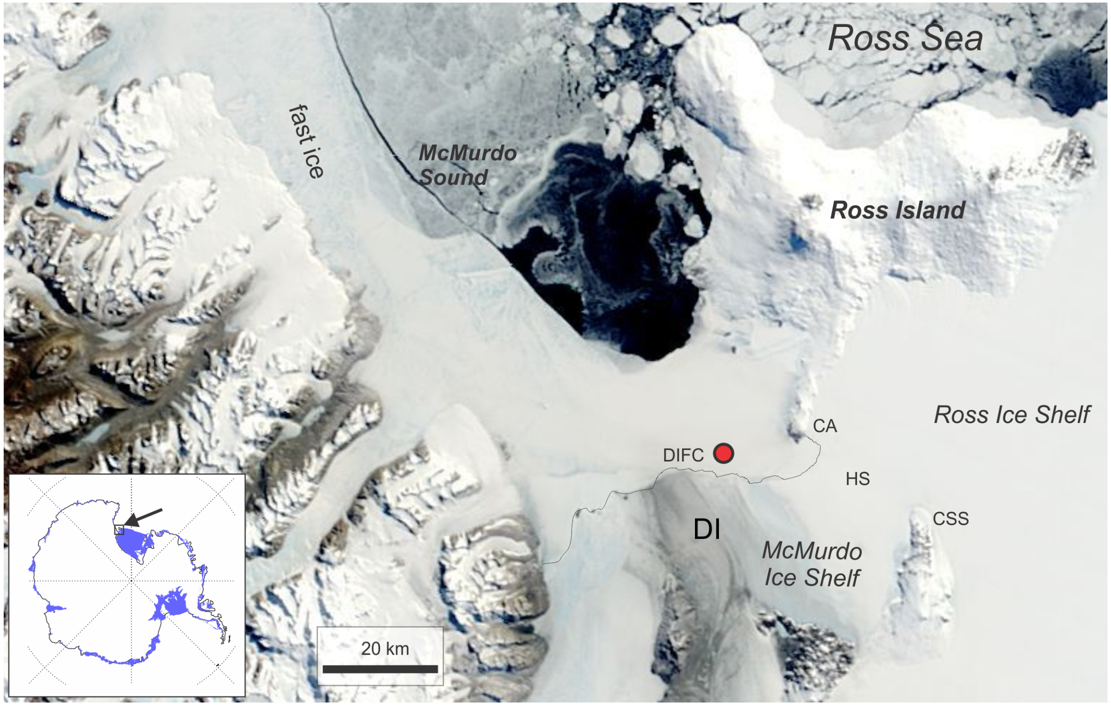

Fig. 1. Revised Fig 1 - Location details...

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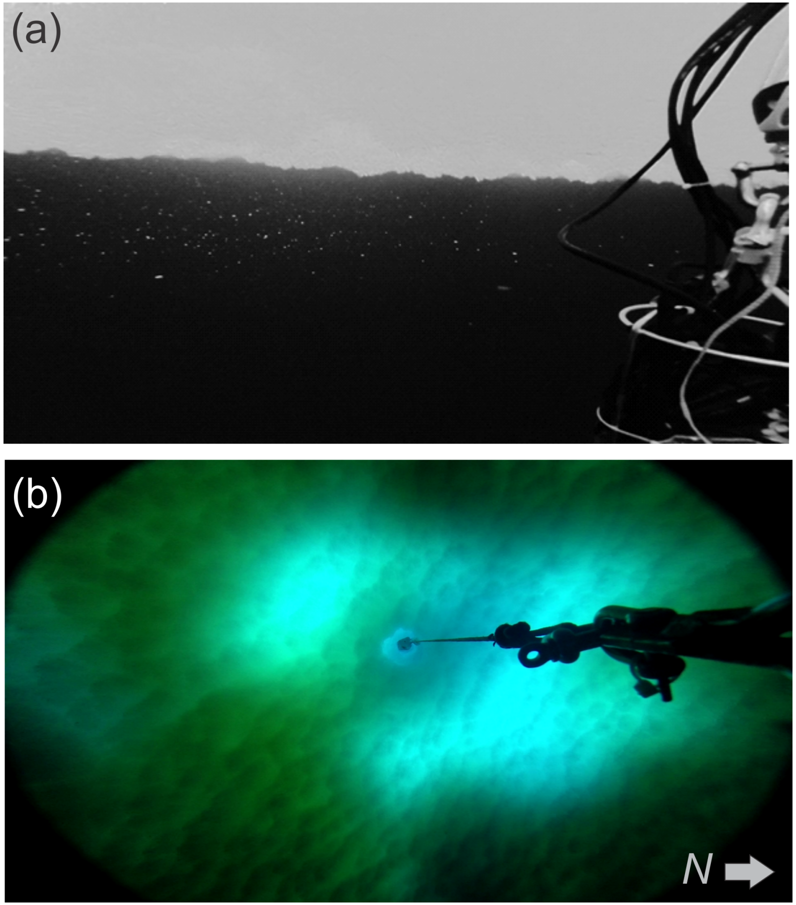

Fig. 2. Fig 5 with new panel (b) relating to improved text.

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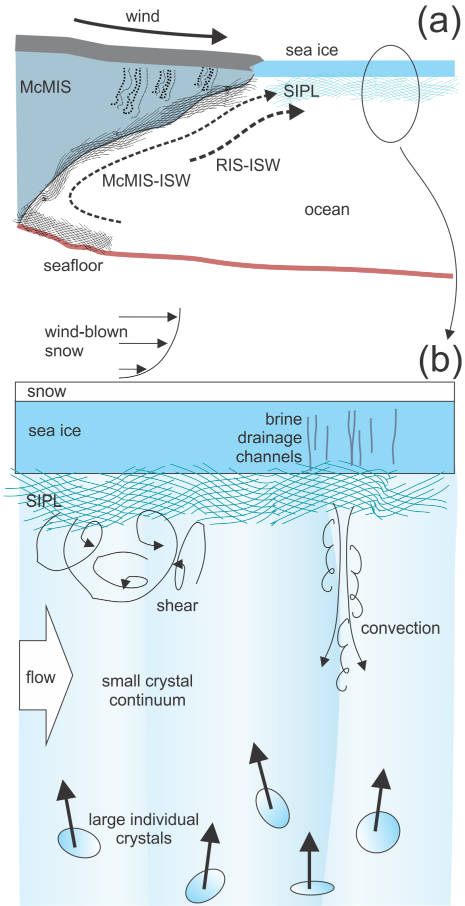

Fig. 3. Revised Fig 12 to account for removed sediment section

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