Final Author Comments - responses to Reviewer 2 comments

21 April 2021

1 Responses to Reviewer 2 Comments

We thank Reviewer 2 for their comments on our submission as a Brief Communication within criteria (c): "to disseminate information and data on topical events of significant scientific and/or social interest". We provide the following responses to the points they have raised.

Reviewer 2 commented generally that the breaking mechanism of fast ice was not discussed adequately in the manuscript. As noted in our Final Author Comments on Reviewer 1's comments, we agree with both reviewers that further discussion of fast ice break out mechanisms would be valuable additions to the manuscript and we will look to include an expanded discussion on breakout mechanisms in the revised manuscript. We have responded to the general comments of both reviewers in our Final Author Comments on Reviewer 1's comments, and included our responses here for completeness.

We agree with both reviewers that further discussion of fast ice break out mechanisms would be valuable additions to the manuscript and will look to include an expanded discussion on breakout mechanisms in the revised manuscript that will include:

1.) Describing how offshore surface winds in McMurdo Sound activate the McMurdo Sound Polynya (MSP), which influences the fast ice cover in the sound. This discussion will reference the findings of Ebner et al. (2013) regarding surface wind forcing and polynya opening and draw on the findings of Dale et al. (2017) who found strong negative correlations between sea ice concentration (SIC) and AWS wind speed data within the Ross Sea Polynya (RSP), which they attributed to strong winds causing advection of sea ice in the region. Dale et al. (2017) also observed that a rapid decrease in SIC during a strong wind event was followed by a more gradual recovery in SIC. The MSP is proximal to the RSP and typically activates under the same strong offshore (southerly) wind conditions.

2.) A brief investigation of other potential breakout mechanisms, including thermodynamic, as referenced by Reviewer 1, and sea swell, as referenced by Reviewer 2, as a potential breakout mechanism. Regarding themodynamic drivers, we note that the entire water column in McMurdo Sound during winter is characterised by cold and very cold (supercooled) water outflow from underneath the McMurdo Ice Shelf (Leonard et al., 2006), and the water column is nearly isothermal and very close to its freezing point (Lewis and Perkin, 1985; Mahoney et al., 2011). During summer, surface waters flowing into the sound from the northeast exhibit higher temperatures (above the freezing point but mainly below 0 °C) (Robinson et al., 2014), but this is not the case during the months this study examines. Regarding sea swell, we agree that a study of sea swell effects on McMurdo Sound fast ice would be profitable. However, we note that there was no sea swell data available during the period of our study, as the frequency at which the sea level was recorded by the tide gauge was not sufficient to resolve waves. Thus, the available data in the region and the scope of the manuscript did not allow us to study the effect of sea swell on the McMurdo Sound fast ice in 2019 or the synoptic weather patterns associated with the AWS data. We agree with Reviewer 2 that due to the absence of fetch upstream of the fast ice in the direction of the wind, no significant swell can be formed prior to the polynya having opened. We note that previous studies on fast ice break up in Antarctica did find that the fast ice broke without a clear association to a wave event (Voermans et al., 2020).

We make the following response to the specific comments from Reviewer 2 below. Reviewer comments have been italicized for clarity.

R2 comment:

The 2019 anomalous breaking of fast ice appears to be associated with KWI and sea ice concentration, as shown in Figure 3. However, this manuscript did not explain the mechanism of fast ice breaking. What mechanism do the authors consider for the fast ice break up by the katabatic wind? Figure 3 showed that the KWI increase coincides with the fast ice break up. When the KWI was large, strong winds were blowing from the south (continent). Again, how does the fast ice is broken by this wind? It is widely known that sea swells affect the breaking of fast ice. The swell effect was also discussed in Banwell et al. (2017), cited by the authors. It seems hard to destroy fast ice only by katabatic wind, even if it is a strong wind. Furthermore, since the wind blows from the shore to the offshore, it is expected not to generate swells that destroy the fast ice.

Our response:

We agree with Reviewer 2 that due to the absence of fetch upstream of the fast ice in the direction of the wind, no significant swell can be formed prior to the polynya having opened. Previous studies on fast ice break up in Antarctica did find that the fast ice broke without a clear association to a wave event (Voermans et al., 2020), additionally, clear relationships between polynya opening and offshore winds have been found (Ebner et al., 2013; Dale et al., 2017). Without wave data, we cannot speculate on the causes of the fast ice breaking beyond the observation that it is correlated with high strong southerly surface winds, as discussed in the manuscript.

However, we strongly suggest that the drag force due to a strong offshore wind blowing over the surface of the fast ice, particularly early in the season when it is relatively thin, can advect the fast ice to the north, and coupled with secondary effects (such as thermal cracking, etc.), can lead to the break-up of the fast ice cover, e.g. Bogardus et al (2020). Once the fast ice cover thickens and strengthens later in the season, we hypothesise that it becomes strong enough to resist this forcing (see lines 111 – 112 in the manuscript). However, as we do not have data on the strength of the fast ice, we are unable test this hypothesis in this study.

R2 comment:

Since the katabatic wind is a strong wind from inside the continent, it is expected that the air temperature will drop during the period when the KWI is large. However, as is clear from Figure 3, the temperature rose when the KWI is large. Please explain the reason for this. Is this because of the breaking of fast ice or a coastal polynya formation? Both of them will increase heat flux from the ocean to the atmosphere.

Our response:

We provided the reasoning for this in the manuscript (lines 75 – 79), which we have stated again here for completeness: "These winds are typically connected to warm temperatures and low air pressure (e.g. Coggins et al., 2013; Chenoli et al., 2013). During winter, higher wind speeds (above 4 – 6 m s^{-1}) increase the mixing between the cold surface inversion layer over the ice shelf and the warmer overlying atmosphere (Cassano et al., 2016). The increase in temperature may also be partly influenced by the Föhn effect, whereby katabatic winds from the Transantarctic Mountains, one of the sources of southerly winds on the Ross Ice Shelf (Parish et al., 2006), experience adiabatic warming." We believe this sufficiently explains why surface air temperatures rise during katabatic wind events.

R2 comment:

Regarding the fast ice break up during June – July: The reviewer cannot know the details because the authors only show the southerly wind component, but wondering the influence of low pressure rather than the katabatic wind from the following facts: the wind speed increased, the temperature rose, and the atmospheric pressure decreased (Fig. 3). If so, the reviewer considers that fast ice could be collapsed by sea swell. The authors also described it as a "storm event" in their conclusion (P. 4, L. 108). Is this an atmospheric event due to the katabatic wind only? Otherwise, is it the effect of a low-pressure system? Please clarify this.

Our response:

We addressed the comment on sea swell as a potential fast ice break up mechanism in a previous response. Here we focus our response on whether a “storm event” is due to katabatic winds only.

The scope of our brief communication manuscript and the available data did not allow for us to attempt to partition the strong southerly surface winds we observed into synoptic and katabatic components. The strong southerly wind events in McMurdo Sound, associated with low pressure and rising air temperatures, are linked to the Ross Ice Shelf Air Stream (RAS), which is forced by synoptic low pressure systems along the coast and fed by katabatic winds near the grounding zone of the Ross Ice Shelf. The RAS is known to occur frequently during winter. A detailed description of this phenomenon would be beyond this brief communication, but we refer Reviewer 2 to Dale (2020) for a discussion for the RAS and its effect on polynyas. We used the term storm event because our KWI index is not based on wind speed and thus we cannot speak of a strong wind event. Specifically, we do not use the wind speed data directly to define the KWI as there are known issues with topographical steering at the Scott Base measurement site, as well as general issues with rime and snow cover interfering with AWS wind measurements in polar regions (Ebner et al., 2013).

Further, strong southerly winds, for which the KWI is used as a proxy, are not in all cases associated with katabatic winds, although that is how they are commonly referred to, which is why we do not speak of katabatic wind events in the manuscript. Katabatic winds play a role in forming the RAS. For a discussion on the link between synoptic winds, katabatic winds and polynya opening, we refer Reviewer 2 to Ebner et al. (2013) who show a clear link between offshore winds (both of synoptic and katabatic origin) and polynya opening. With this said, however, we take onboard the reviewer’s concern with our description of the origin of the wind-induced break-up, and acknowledge that the "Katabatic Wind Index" may not be the best name for this index. We will, therefore, rename the index to something along the lines of a "Modified Storm Index" in the revised manuscript to reflect this. This name references directly the origin of the index in Brunt et al. (2006), as well as the modifications we have applied to be able to utilise the index for discrete events. We note that Brunt et al. (2006) found that "... the characteristics of weather conditions most influential in breaking up fast ice... [were] characterized by the simultaneous occurrence of low pressure and an anomalous temperature".

R2 comment:

This study showed a relationship between a coastal polynya and KWI (section 4). By what mechanism does the polynya cause the fast ice break up? Is it just a description of a relationship between KWI (southern wind) and polynya? The air temperature was below -10 degrees Celsius during the period. Under such atmospheric conditions, even if an open water fraction appears by the divergent ice motion due to prevailing wind, the ocean surface will be immediately covered with thin sea ice. In winter, coastal polynyas should be considered as thin ice-covered areas with high ice concentration rather than low ice concentration areas under the passive microwave sensor’s coarse spatial resolution. Many sea ice concentration algorithms used for passive microwave satellite data underestimate the concentration in thin ice-covered areas. It may be possible to regard the low ice concentration region as a coastal polynya signal due to this characteristic, but caution will be required. It does not detect coastal polynyas precisely. For the detection of coastal polynyas from passive microwave satellite data, Tamura et al. (2007; 2008) and Nihashi and Ohshima (2015) would be helpful.

Our response: We thank Reviewer 2 for highlighting the challenges in using passive microwave satellite data to identify polynya area, and for providing three references that provide information on the development of microwave thin ice algorithms and their application to polynya detection. We will describe this in the revised manuscript and reinforce that coastal polynyas cannot be precisely detected using microwave-derived sea ice concentrations. We also refer Reviewer 2 to Ebner et al. (2013) who used a combination of passive microwave and MODIS data to identify polynyas in their study. They stated that “The two main problems when getting the correct POLA from MODIS data are the spatial coverage of the daily composites and the errors in cloud detection over sea ice in winter. If the main polynya region in the MODIS composite is covered by clouds, an underestimation of POLA is unavoidable, even with the applied correction method. A false detection of clouds can strongly influence the MODIS thin-ice retrieval and, hence, influence the POLA signature. On the other hand, a main problem of AMSR-E data is the relatively coarse horizontal resolution (6.25 km). Small-scale polynyas are not resolvable with this resolution and, hence, the AMSR-E data tends to underestimate the POLA compared to the MODIS thin-ice thickness approach. In addition, thin ice-covered polynyas may be undetected by AMSR-E.” (Ebner et al., 2013) (Note that POLA refers to “polynya area”.) Hence, we acknowledge that both MODIS and AMSR-E have issues in detecting polynyas, but note that we found good agreement between the two products in this study, as well as with our manual interpretation of SAR imagery, giving us confidence that we can use these products effectively to detect the presence of polynyas.

Regarding the connection between the polynya opening and the fast ice break up, we believe that they are both driven by the same process, i.e. the strong southerly (offshore) surface winds.

2 References

Bogardus, R., Maio, C., Mason, O., Buzard, R., Mahoney, A. and de Wit, C.: Mid-Winter Breakout of Landfast Sea Ice and Major Storm Leads to Significant Ice Push Event Along Chuckchi Sea Coastline, Front. Earth Sci., https://doi.org/10.3389/feart.2020.00344, 2020.

Brunt, K. M., Sergienko, O., and MacAyeal, D. R.: Observations of unusual fast-ice conditions in the southwest Ross Sea, Antarctica: preliminary analysis of iceberg and storminess effects, Annals of Glaciology, 44, 183–187, https://doi.org/10.3189/172756406781811754, 2006.

Dale, E.: Interactions Between Changing Weather Patterns and the Antarctic Cryosphere in the Ross Sea Region, PhD Thesis, University of Canterbury, New Zealand, 2020.

Dale, E. R., McDonald, A. J., Coggins, J. H. J., and Rack, W.: Atmospheric forcing of sea ice anomalies in the Ross Sea polynya region, The Cryosphere, 11, 267–280, https://doi.org/10.5194/tc-11-267-2017, 2017.

Ebner, L., Heinemann, G., Haid, V. and Timmermann, R.: Katabatic winds and polynya dynamics at Coats Land, Antarctica, Antarctic Science, 26(3), 309-326, https://doi:10.1017/S0954102013000679, 2013.

Leonard, G H., Purdie, C. R., Langhorne, P. J., Haskell, T. G., Williams, M. M. J., Frew, R. D.: Observations of platelet ice growth and oceanographic conditions during the winter of 2003 in McMurdo Sound, Antarctica, J. Geophys. Res., 111, C04012, doi:10.1029/2005JC002952, 2006.

Lewis, E. L. and Perkin, R. G.: The Winter Oceanography of McMurdo Sound, Antarctica. In Oceanology of the Antarctic Continental Shelf, S.S. Jacobs (Ed.), https://doi.org/10.1029/AR043p0145, 1985.

Mahoney, A. R, Gough, A. J., Langhorne, P. J., Robinson, N. J., Stevens, C. L, Williams, M. M. J., and Haskell, T. G.: The seasonal appearance of ice shelf water in coastal Antactica and its effect on sea ice growth, J. Geophys. Res., 116, C11032, doi:10.1029/2011JC007060, 2011.

Robinson, N. J., Williams, M. J. M., Stevens, C. L., Langhorne, P. J., and Haskell, T. G.: Evolution of a supercooled IceShelf Water plume with an actively growing subice platelet matrix, Journal of Geophysical Research: Oceans, 119, 3425–3446, https://doi.org/10.1002/2013JC009399, 2014.

Voermans, J., Rabault, J., Filchuk, K., Ryzhov, I., Heil, P., Marchenko, A., Collins, C., Dabboor, M., Sutherland, G., and Babanin, A.: Experimental evidence for a universal threshold characterizing wave-induced sea ice break-up, The Cryosphere Discussions, pp. 1–24, https://doi.org/10.5194/tc-2020-201, 2020.