Thanks to the reviewers for their helpful comments that have improved this manuscript. Responses to reviewers are in italics. Changes to text or figure captions are denoted by ***bold italics*** *and the line numbers given refer to the modified manuscript that does not include tracked changes.*

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Anonymous Referee #1

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This paper uses the CESM Large Ensemble to simulate possible floe tracks and floe thermodynamics throughout the course of MOSAiC. It suggests that the model tracks can assist with campaign planning and put the observations into context. The paper is very well written, easy to follow, and provides clear graphics. Nevertheless, I unfortunately have severe doubts whether it really is suitable for publication in The Cryosphere. This is primarily because the relevance of the paper is somewhat unclear given its current framing.

1. If this really is meant as a guidance document to help campaign planning for MOSAiC, it probably is best communicated to the MOSAiC planning staff rather than published as a scientific paper. However, for this particular purpose, seasonal prediction systems initialized with the currently observed sea-ice state of the Arctic seem much better suited than a free simulation from a coupled climate model. It is my understanding that such system is in place to help the planning of MOSAiC, which by now is based on 45,000 individual simulations (see https://www.polarprediction.net/yoppactivities/sidfex/ for details).

We appreciate a great deal of work has gone into planning the MOSAiC campaign from determining a starting location to forecasting conditions, and we now better acknowledge that work within the manuscript. In particular, Thomas Krumpen of AWI has done a substantial amount of work to determine a likely starting location, and his suggested location was used as a foundational assumption for this paper. This is now more clearly acknowledged in the manuscript. We also do not intend this work to be a forecast of the actual conditions MOSAiC will encounter during its year-long drift, and the reviewer is correct that initialized forecasts would be the correct tool for that purpose. Our goals for this work are distinct from this guidance. The intent of this manuscript is instead a scientific analysis that provides context on possible measurements in light of internal variability and a changing climate state. We also demonstrate how free running climate model simulations can both be evaluated in a consistent way with observations as well as investigate ways in which a climate model might assist with future campaign planning. We have substantially revised the manuscript (as shown below in the bold text) to better reflect these goals throughout the paper. Because of the scientific focus, we believe that the manuscript is suitable for publication in The Cryosphere.

Our definition of planning is broad and taken to be providing information to the MOSAiC observational teams as they prepare to deploy and plan field strategies. In this sense, we have made deliberate efforts to communicate the results to the MOSAiC teams and work with them on particular questions they may have. This manuscript is primarily related to sea ice observations. Co-author Perovich is one of the Sea Ice Team leads for MOSAiC and co-author Webster is involved in Sea Ice remote sensing as part of MOSAiC and have been integral in some of the analysis presented because it is useful for their planning. In addition, these results have been presented at the NOAA ESRL laboratory in Boulder, CO to a number of MOSAiC participants *and planners including Matt Shupe, who is one of the Atmospheric Team leads as well as a Coordination co-lead. Since the manuscript reviews have come back, we have been back in touch with several of the MOSAiC planning team members to be sure we can adequately reflect and reference their contributions, and we have made changes to the text to reflect these conversations.*

However, the audience for this work is also the community at large, not just MOSAiC planners. We have added text contrasting an initial condition climate model ensemble with an initialized forecast to help clarify why we use the CESM-LE as a tool. The world we have observed is just one of many possible "worlds" in terms of the climate response to external forcing, and this is due to the inherent internal variability in the climate system. A free running climate model cannot and should not be expected to replicate observations since it is just one realization of possible climate response to external climate forcing. In past studies, observations were often compared directly with a single climate model experiment. Thus, we focus on the range of possible conditions and how the observations might fit into these as a way of more intelligently assessing and improving a free running climate model. In the past we have also seen numerous comparisons between SHEBA observations and polar-cap model averages, and here we investigate if this is an appropriate comparison (it is not). It is important to share these results with the wider community, some of whom will no doubt use MOSAiC observations when analyzing climate models.

As shown below, we have substantially changed the wording in the introduction and methods section and added to the discussion in order to 1) make the purpose of the study clear and distinct from other MOSAiC planning and 2) to clarify why the CESM-LE is the best tool for the analysis presented. We also now refer to the colored tracks shown on Fig. 1 as "representative" conditions rather than "likely" conditions to help clarify this is not a forecast track.

<u>Introduction – Lines 48-72</u>

In autumn 2019, the icebreaker RV Polarstern will be frozen into the Siberian Arctic with the aim of traversing the Transpolar Drift current over the following year. Extensive analysis using historical satellite data with the IceTrack Lagrangian approach (Krumpen et al., 2019) has been performed in order to identify MOSAiC's starting location, assist with logistical planning, and coordinate research efforts (Krumpen, 2019). Throughout the duration of the experiment dynamical sea ice forecasts, initialized with and assimilating the most up to date ice and weather data, will be performed for the particular MOSAiC track (Kauker, 2019). Analyses of an observationally-initialized ensemble forecast can provide skilful forecasts for MOSAiC conditions and information about how long these forecasts are skilful before the system diverges from the initial state. These types of in-depth observational and observationally-initialized forecast analyses are necessary and important for a successful campaign (IASC, 2016).

In recent years there has been increasing awareness of the impact of internal climate variability on the possible range of sea ice conditions and the resulting representativeness of a single year of observations (Swart et al., 2015; Jahn et al., 2016). In this study, we use data from the Community Earth System Model (CESM) Large Ensemble (CESM-LE) project (Kay et al., 2015). The CESM-LE is an initial condition ensemble, meaning that each ensemble member represents one possible response of the climate system to the external forcing given inherent internal climate variability. The ensemble mean of the individual model experiments represents the response to the changing external forcing, whereas the difference of each ensemble member from to the ensemble mean provides a measure of internal variability. Using

the Lagrangian Ice Tracking System (LITS; DeRepentigny et al., 2016), we derive the tracks of virtual sea ice floes for each ensemble member and the evolution of floe conditions over a calendar year. This analysis is not equivalent to examining observational tracks over time. Observational tracks are affected by both internal variability and forced change. Instead, the CESM-LE is an ideal tool for disentangling the effects of internal climate variability from forced change on the conditions a field campaign might encounter.

The purpose of this study is not to provide a forecast for the particular sea ice conditions during MOSAiC. Instead, we use the likely starting condition determined by the MOSAiC planners to address three fundamental goals: (1) offer insight on the representativeness of MOSAiC observations given the range of internal climate variability; (2) provide guidance about what types of observations can best assist with model improvement and appropriate ways these observations can be used to improve climate models; (3) show how free running climate model simulations might assist with future campaign planning.

Methods – Lines 77-95

The CESM-LE is a publicly available initial condition ensemble and is designed to assess the role of internal variability in the presence of forced change within the climate system. Each of the 30 CESM-LE members uses an identical code base and external historical and future climate forcing. The ensemble members are unique due to round-off level temperature differences (10^{-14}K) in the initial atmospheric conditions in 1920. Over time these round-off level differences lead to chaotic evolution in the climate system akin to the initial condition impact on weather forecasts (Lorenz, 1963). Therefore, the spread in individual CESM-LE members is generated solely by internal climate variability. Comparisons between ensemble members allow us to better understand and contextualize the range of possible floe tracks, sea ice conditions, variability, and predictability.

Climate models evolve freely, so they cannot and should not exactly represent the observed historical Arctic conditions. Therefore it is not possible to validate a model by comparing a single climate simulation to the observations, nor is it appropriate to directly compare the observations to an ensemble mean as by design the ensemble mean has damped internal climate variability (Kay et al., 2015). The CESM-LE well captures the Arctic sea ice historical state and trends, and the mean state compares best to the observations relative to other Coupled Model Intercomparison Project Phase 5 (CMIP5) experiments (Barnhart et al., 2015; Jahn et al., 2016). Few other CMIP5 models contribute multiple ensemble members and none had enough members to adequately quantify the internal variability in Arctic sea ice. In this way, the CESM-LE is unique because it does sufficiently represent the spread in conditions associated with internal climate variability (Jahn et al., 2016). The CESM-LE also reasonably represents the pattern and magnitude of Arctic sea ice thickness (Labe et al., 2018). The CESM-LE sea ice motion patterns are similar to observations, though the Beaufort Gyre circulation is stronger than observed (DeRepentigny et al., 2016). Thus, due to its well represented Arctic sea ice mean state and variability and the availability of many ensemble members, the CESM-LE is an ideal global climate model for the following analyses.

Representative track discussion – Lines 146-162

These maps are also used to identify "representative" tracks (Fig.1, coloured lines) by identifying locations with high track counts that also formed a continuous path – i.e. a path in which unphysical "jumps" in the track were not permitted. It is important to note this is not a forecast of the likely path MOSAiC will take, but instead is meant to represent a reasonable

path given the individual tracks from ensemble members under the same climate forcing and how these may differ between Seasonal and Perennial conditions. While all representative tracks follow a Transpolar Drift trajectory, the representative Seasonal path is longer and shifted further towards the Canadian Arctic compared to the representative observed and simulated Perennial paths, which end further north (Fig. 1). … All three representative tracks enter the satellite "gap" in December, but the difference in when the representative tracks exit the "gap" differs between September for observational and Perennial tracks and July for Seasonal tracks.

<u>Discussion – Lines 244-253</u>

The CESM-LE is a fully coupled global climate model with well represented Arctic sea ice mean state and variability. As an initial condition ensemble, the CESM-LE is a tool designed to explore the effects of internal climate variability and forced change. Thus, by tracking modelled sea ice floes using the CESM-LE characteristic Perennial and Seasonal sea ice conditions, we have an ideal framework to meet our three goals: (1) put into context a single year's observations since MOSAiC will represent a single response of the climate system to forced change; (2) provide guidance about observations that can be used to improve climate models; (3) demonstrate how free running climate models might assist with future campaign planning.

Substantial work by MOSAiC planners has gone into both determining a starting location (85°N, 125°E) for the campaign and developing a forecast system for the campaign once it has initialized. This study is not intended to provide a forecast for the campaign, and we leverage the likely starting location and examine the range in CESM-LE conditions to contextualize the MOSAiC campaign.

<u>Discussion – Lines 269-274</u>

MOSAiC observations will focus on coupled processes, so using a coupled climate model to analyse the representation of these coupled processes provides data that traditional weather or process modelling does not. While higher resolution coupled regional models can also provide information on modelled coupled processes, they do not have a direct linkage to extra-polar regions present in a global climate model important for understanding the exchanges between (both into and out of) the Arctic and elsewhere. To this end, we explore how the CESM-LE results can inform data collection during MOSAiC as well as how modelers can optimally use the data once the campaign is over to improve models.

2. The same holds for the assessment of "likely sea-ice conditions that the campaign will encounter during the year-long experiment". An initialized seasonal prediction system continuously updated until the start of MOSAiC likely provides more robust answers than a coupled, free simulation.

We believe this is a miscommunication about the purpose of this work. We are not providing a forecast, which we agree would be better informed by a tool like an initialized seasonal prediction system. However, we believe the free running climate model ensemble is another important tool that can provide different types of information relevant to the experiment or future, similar experiments. Please see the sections of the text highlighted in the response to point 1.

3. I must admit that I also failed to fully grasp the relevance of the discussed virtual floe track and floe evolution in a perennial ice cover. Maybe somewhat more discussion could be provided to

explain why this discussion is included, given that the perennial ice cover discussed here no longer exists. These are just my initial reactions after reading the paper. However, maybe (hopefully!) there's been a misunderstanding. In this case, I hope that the authors can sharpen the arguments for the overall framing of this paper.

One purpose of this work is to use a climate model to provide context to the observations obtained during the campaign in Seasonal conditions. To fulfill this goal, it is important to use Perennial conditions to contrast Seasonal conditions. For example, if we examined Seasonal tracks only we would see that a number of paths enter the Beaufort Gyre but we would not know if that path became more common with time as the climate system responding to greenhouse gas forcing or if it was just a model bias. By contrasting with the Perennial conditions, we found that these tracks appear to be related to the climate system response, though we did find that even in Perennial conditions the Beaufort Gyre is too strong. Using climate models enables this type of analysis and is informative because it is possible to examine changes in the mean state as well as the distribution of conditions. This can be seen in the Figure below, where we could have distributions of conditions in the Perennial and Seasonal conditions and see if the distribution has shifted, broadened, etc. Changes to the distribution of conditions could impact both modelers' and observationalists' expectations for the sea ice and also may suggest ways in which observations would be most useful for improving models. To make the purpose of using the Perennial conditions clear we've included the following in the text.

***Lines 109-111**: The purpose of including Perennial conditions, which no longer exist in the present-day Arctic, is to act as a contrast to the Seasonal conditions in terms of how the mean state and variability, or spread in conditions, has changed over time.*

Figure (Courtesy of Alexandra Jahn, University of Colorado Boulder)