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Interactive comment on "Exploring the utility of quantitative network design in evaluating Arctic sea-ice thickness sampling strategies" *by* T. Kaminski et al.

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We thank the reviewers for their very constructive and highly valuable comments.

Both reviewers have highlighted the novelty of the study and its merits.

In the following we address their comments in chronological order. A revised version of the manuscript is included as supplement.

Response to Comment by Referee 1

The referee's main comment relates to the dependency of the study results on the model, its process representations and spatial resolution. We describe below (response to specific comment 4) how we addressed this point.

Below we address the referee's specific comments one by one:

1. Section 2.2: : We added the following paragraph (printed here in **bold face**) on the method in general, but also stressed that the cost function minimisation is not performed (i.e. no assimilation) in this study.

The minimum of Eq. (1) achieves a balance between the observational constraints and the prior information. This variational approach to assimilation guarantees (in contrast to sequential approaches) full consistency with the model dynamics. For our model this means that we infer a trajectory through the state space that assures conservation of mass, energy and momentum (except at the lateral domain boundaries). We note that, in this QND study, no minimisation of Eq. (1) is required.

2. Section 2.3: : We elaborated by adding a discussion of Eqs (3) and (4) and by referring to the results section for examples.

3. Prior Uncertainty : Yes! The assessment of prior uncertainty is always difficult, and it may be that we are too optimistic for some control variables and too pessimistic for others. But we think this is not important in the context of our study, as we explain in the following paragraph that has been added to Section 3.2:

As the QND approach does not require the minimisation of Eq. (1), the prior uncertainty only serves as a reference such that the impact of observations is quantified in terms of a percentage change relative to the prior uncertainty (uncertainty reduction). If the prior uncertainty was too optimistic the impact of the observations would be underestimated, and, vice versa, if the prior uncertainty was too high the impact of the observations would be overestimated. As we will use the same prior uncertainty as the reference for all observational configurations, their relative performance is not affected.

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4. Processes and resolution : We extended the discussion by the text indicated in **bold face**.

We note that the afore-mentioned model uncertainty to be provided to the tool does not necessarily need to refer to the specific model that is used. As long as the response functions of our model are approximately correct, we can use the present system to simulate the observational impact on an assimilation system around a different model. For QND results to be valid beyond the model at hand, one has to employ a well-validated model that includes all relevant processes. **For example the model should have adequate sensitivity of regionally integrated ice properties with respect to the initial ice thickness. For the model used here this sensitivity is similar for resolutions from 1/2 to 1/12th degree. One would not expect a drastic change of this sensitivity when moving to even finer (eddy permitting) scales, but this requires further investigation. Computationally, the current 126 dimensional control space requires 127 model simulations (over five months each) for the approximation of the Jacobian matrices (M' of Eq. (3) and N' of Eq. (4)) quantifying observational and target sensitivities. This should be feasible even for high-resolution models.**

All modifications suggested in the technical comments 1-4 were implemented. The limited readability of Figures 5, 8, and 11 has been improved through better labeling and more text where the first sensitivity plot (Fig 5) is introduced (see response below to detailed comment # 4 of Referee # 2).

Response to Comment by Referee 2

We first address the major comments:

1. Model Description: We extended the description of the model, with particular focus on ice and snow processes. Among other extensions, the following paragraph was added:

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A dynamic-thermodynamic sea ice model with a viscous-plastic rheology (Hibler, 1979) is coupled to the ocean model. The prognostic variables of the sea ice model are ice thickness, snow depth, and ice concentration. Ice drift is calculated diagnostically from the momentum balance. Snow depth and ice thickness are mean quantities over a grid box. The thermodynamic evolution of the ice is described by an energy balance of the ocean mixed layer following Parkinson and Washington (1979). Freezing and melting are calculated by solving the energy budget equation for a single ice layer with a snow layer. When atmospheric temperatures are below the freezing point, precipitation is added to the snow mass. The snow layer is advected jointly with the ice layer. The surface heat flux is calculated through a standard bulk formula approach using prescribed atmospheric data and sea surface temperature predicted by the ocean model. Owing to its low heat conductivity the snow layer has a high impact on the simulated energy balance (Castro-Morales et al., 2014). The sea ice model is formulated on the ocean model grid and uses the same time step. The models are coupled following the procedure devised by Hibler and Bryan (1987).

2. Study Period: We extended the motivation for the choice of the period in section 3.1 which defines the target quantities. The extension is printed in **bold face**:

The goal of this study is to explore the utility of the AOND system in guiding observations for short-term to seasonal-scale sea-ice predictions. Ice forecasting at these time scales has been identified as a high priority in the context of safe maritime operations (Richter-Menge and Walsh, 2012; Kurtz et al., 2013a; Eicken, 2013) management of marine living resources (Robards et al., 2013) and food security for indigenous communities (Brubaker et al., 2011). Here, we focus on the first two issues in the Chukchi and Beaufort Seas north of Alaska (Figs. 1 and 2), which are experiencing some of the highest reductions in summer ice concentration anywhere in the Arctic, along with major offshore hydrocarbon exploration and potential impacts on protected species such as walrus (Eicken and Mahoney, 2015). Thus, the selection of target quantities for the AOND system seeks to evaluate and improve predictions aimed at the information needs of stakeholders and resource managers for this region. **Of particular interest is the summer season with its reduced ice cover. From an observational point of view this period is particularly challenging, as surface melt and its impact on ice dielectric properties complicate retrievals of variables such as snow depth and ice thickness through satellite remote sensing. For this study we deliberately selected the year 2007, a year of particularly low ice extent, which may be regarded as representative of future ice conditions in a rapidly changing Arctic. As is detailed below, we study both, predictions for selected days and for integrals over selected time periods.**

3. Prior Uncertainty: Referee # 1 also addresses this point (specific comment # 3) and we refer to our response above. We note in addition that we deliberately refrained from using satellite observations to reduce prior uncertainty on the initial state, because we wanted, as reference, a control vector that did not yet include such observational information.

4. Sensitivity Analysis: Each of the sensitivity figures displays a complete matrix N' for a particular target quantity. To clarify this, we added the text in **bold face** (and removed Fig. 5c as suggested):

Figure 4 provides a visualisation **of the complete matrix** N', which shows the response of the three target quantities to a change in each of the control variables by one SD of the prior probability density function (Table 1). **The position on the x-axis corresponds to the number of the control variable in the last column of Table 1.**

And we also improved the readability of the sensitivity figures through better labels.

5. Target Quantities on specific days: We note that, even though some of the target quantities do refer to specific days, the results appear to be robust with respect to a shift in the target day, as is described in the case of the NOB target region and predictions for August 10 and August 31.

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To clarify this point we have added the following sentence to the discussion:

A consequence of this robustness is that the specific target days we chose, only play the role of a typical day within a longer time period.

6. Applicability to Regional Scale: The reviewer is correct, and we modified the statement by adding the text in **bold face**:

Furthermore, rather than operating Arctic-wide, the same concept can be applied on smaller regional scale**, when the forecasting period is short enough to ensure that the main influence factors can be appropriately simulated within the model domain.**

Now we address the minor comments:

1.-3 Grammar and SD: All fixed.

4. and 6. Figures: Modifications made.

5. Effect on Concentration in Chukchi: Many thanks for pointing at this effect. We included extra text into the results section:

The impact of the B2F transect on the 10 day forecast of ice concentration over the (remote) Chukchi target region (panel b of Figure 3) is remarkable. It is explained by the relatively high impact of the lead closing parameter h_0 in the formulation of freezing (control variable # 89) on ice concentration (Figure 4). Since h_0 is a global parameter, observations on both transects can help to reduce uncertainty in this parameter.

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Please also note the supplement to this comment:
http://www.the-cryosphere-discuss.net/9/C1/2015/tcd-9-C1-2015-supplement.pdf

Interactive comment on The Cryosphere Discuss., 9, 1735, 2015.