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Interactive comment on "Assisting the Evolution of the Observing System for the Carbon Cycle through Quantitative Network Design" *by* Thomas Kaminski and Peter Julian Rayner

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We thank the reviewers for their constructive comments on the manuscript. In the following we address their comments point-by-point. We use *text in italics* to repeat the reviewer comments, normal text for our response, and **bold faced text** for quotations from the manuscript, with changes marked in colour.

We provide the revised manuscript (with and without changes highlighted) in the supplement.

1 comments by Anonymous Referee #1

- *Title of the manuscript*
  This manuscript describes advances in the use of Quantitative Network Design (QND) to analyse carbon cycle observing systems such flask measurements and eddy covariance flux networks. The paper ends with a brief illustration of the impact of using separate and integrated QND (where "separate" refers to each observing network component is analysed separately and "integrated" refers to analysing the entire system simultaneously). The results indicate that separate QND can lead to significant biases.

  Overall the manuscript is very well written and provides an informative description of QND and its recent evolution and application to carbon cycle problems. The brief analysis of separate vs. integrated QND provides a useful illustration but feels quite incomplete. It is clear – even intuitive perhaps – that separate QND will potentially lead to biases but the fact remains that for many practical purposes integrated QND is likely to be too expensive to use routinely. The key question, therefore, is to ask how bad these biases will be it typical carbon cycle problems. The analysis presented in section 4.2 ("complex analysis") instead looks at the somewhat artificial example where model error is ignored. The authors acknowledge that ignoring model error makes the contrast more drastic.

  The main modification I propose for the manuscript is to include the posterior estimates for the separate and integrated QND when model error is included (in addition to the results already presented). This will help the reader better understand what the practical implications are when making these choices. It is also important that the authors include details about the error values used for the different components rather than just referring to the "tool's default." Perhaps a table detailing each of these.

  We address the points in reverse order:

We added the "tool's default" uncertainties:

For both networks we use the tool's default uncertainty. We , i.e. 1 ppm for flask and 10 gCm^{-2}day^{-1} for flux observations. We first set the model error to zero ...

And added an example that takes uncertainty due to model error into account:

The uncertainty component reflecting model error clearly depends on the quality of the model used. For example, a model that achieves a 20% uncertainty in the NEP simulated over Europe would (based on the 20-year posterior NEP average of 0.39 GtC/yr inferred by Scholze et al. (2007)) have a $\sigma(f_{mod})$ of 0.08 GtC/yr. Using this value in the evaluation of equation (3) , would increase the posterior NEP uncertainties for Europe in the separate QND to 0.30 GtC/yr for the flux network and to 0.22 GtC/yr for the flask network, i.e. according to equation (11) a combined posterior estimate of 0.19 GtC/yr, while the integrated QND would yield a posterior uncertainty of 0.10 GtC/yr, i.e. a factor of two less.

We don't think *integrated QND is likely to be too expensive to be used routinely*. In contrast to a variational assimilation system system around an integrated model, which interatively runs the model and evaluates gradient information, the QND uses a single evaluation of the observational and target Jacobians.

- *I picked up the following small errors:*

  The 2 in CO2 has not consistently been subscripted throughout the manuscript.

  If possible use a multiplication sign instead of an "" to represent multiplication.*

  Line 250: Should this be "XCO2"?

  Line 250: The statement about OCO being the first mission designed to observe atmospheric CO2 is a little misleading. SCHIMACHY was designed to observe CO2, despite what is said later in the manuscript. I think the distinction that the

  authors are trying to make is that the focus of the OCO mission is CO2, whereas SCHIMACHY was designed to observe a range of trace gases.

  Line 290: SDBM Knorr → SDBM; Knorr

  Line 301: BETHY, Knorr → BETHY; Knorr

  Line 357: allowed to change aspects → allowed changes to aspects

  Thanks. All corrected.

2 comments by Anonymous Referee #2

- *The paper is a useful and easy to read reference to the increasing amount of QND. the authors are both experts and adequately describe the basic concepts and summarise the state of the art well.*

  The novelty is the discussion of individual verbs integrated design, even though this is rather simple, as the authors themselves agree. I would like to stress this aspect, as after Paris the scientific world may be faced with having to devise a observation system that can cope with multiple variables (reduction targets, IND's etc). It would be nice to know what implications this would have for QND (think for instance of CO2 reductions and ocean acidification limits).

  For a short list of candidate networks the QND approach typically evaluates multiple target quantities (in many of the examples net and gross fluxes over several regions or even on a grid).

  For the case where the evaluation is combined with a formal optimisation section 2 suggests a procedure: **In case of multiple target quantities, we can minimise a suitable scalar function of their posterior uncertainties, e.g. their sum of squares.**

In the manuscript we now explicitly mention more target quantities like ocean acidification, land-use change fluxes ... and make the link to the Paris agreement clearer.

Below is a revised paragraph of the conclusions but similar extensions were made in the abstract and the introduction:

We demonstrated the need for an integrated QND approach, i.e. jointly in a a joint assessment of all relevant data streams in an integrated model that includes all components required to handle all relevant simulate these data streams. In the last decade there were several demonstrations of the QND approach in a CCDAS, for atmospheric data streams (CO_2 and XCO_2) and for land data streams (direct flux measurements, FAPAR, SIF). This The list of (potential) further direct (e.g. biomass) or indirect (e.g. soil moisture) observational constraints on the carbon cycle is much longer (see e.g. Raupach et al., 2005; Ciais et al., 2014; Scholze et al., 2017)

(see e.g. Raupach et al., 2005; Ciais et al., 2014; Scholze et al., 2017; Dolman et a Our examples also demonstrate that QND assessments can evaluate can assess the complementarity of in situ and satellite observations , as well as real and hypothetical data streams , and complementarity of data streamsfor a range of suitable target quantities. This is exactly what is needed to support guide the evolution of the observing system an observing system that can reduce uncertainties in estimated natural and anthropogenic fluxes, as requested by the Paris Agreement.

- *I have a general, more philosophical, problem with QND that is not completely solved with the quantification of the model error, although it is the main part of the a priori input into the QND. Basically QND assumes that all the key processes are modelled in such a way, that constraining them with data becomes possible. The SIF case presented is an example of that: only after addition of a fluorescence model one can use the data. That means that that we can optimise the network*

only to our current perception of the system (and to the adequate formulation of the target quantities). My feeling is that this uncertainty is not fully covered in the model uncertainty (I think sometimes it is just a convenient way to hide it) and should be stated more explicitly in the paper.

It is not necessary that all key processes are modelled in such a way that constraining them with data becomes possible. In fact we typically face the situation that a part of the processes/parameter space (more precisely a sub space of the control space) remains unconstrained by observational networks we are evaluating. The part of the parameter space then just keeps its (typically large) prior uncertainty.

To better explain what is needed by the QND system and what the limits are, we added the following paragraph to section 2:

To conduct a correct QND assessment, the requirement on the model is not that it simulates the target quantities and observations under investigation correctly, but the requirement is that it provides a realistic *sensitivity* of the target quantities and observations under investigation with respect to a change in the control vector. If these sensitivities, i.e. the Jacobians, are realistic, but the simulation of target quantities and observations incorrect, we can always make a correct QND assessment with appropriately large model uncertainty. The result of the assessment may then be that a particular data stream is not useful in constraining a particular target quantity given current modelling capabilities. In this situation we could operate the QND system with reduced model uncertainty to explore which accuracy of the model is required for a data stream to be a useful constraint on a given target quantity. As an example for incorrect simulation but correct sensitivity we can think of a regional transport model that simulates the small scale variability very well but cannot match the absolute concentration because it runs with a wrong large-scale background. In particular when it comes

to new data streams and target quantities the accuracy of both, the simulation and the sensitivities, are hard to assess. In the case of a model that misses relevant processes we may expect errors in both the simulation and the sensitivities, and consequently also in the QND assessment.