Comparison of model-based geostatistical trawl survey biomass indices with the current design-based estimates for South African hakes
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Summary
This document presents a comparison between model-based and designed-based trawl survey biomass indices for shallow-water hake *Merluccius capensis* and deep-water hake *M. paradoxus* along the West and South Coast of South Africa. For the design-based approach, we followed the protocol to calculate hake biomass indices as used in current stock assessments of hakes. To estimate the alternative model-based biomass indices, we fitted the Geostatistical delta-GLMM (Thorson et al. 2015) to trawl survey datasets, subsetted by species, coast and season. For *M. capensis* the results suggest that the alternative biomass estimates and relative trends are similar, but that the Geostatistical delta-GLMM produced more precise estimates, as judged by the smaller CVs. For *M. paradoxus*, the biomass indices are comparable for the West-Coast, but for the South Coast the geostatistical point estimates were substantially larger than the design-based point estimates. The latter also resulted in notable distortion between the relative abundance trends. Whereas the model-based West Coast CVs were consistently smaller than the design-based CVs for both species, the South Coast CVs for *M. paradoxus* were inflated relative to the design-based estimates.

Introduction
Winker et al. (2017) proposed exploring the geostatistical delta-GLMM (Thorson et al. 2015) as alternative model-based framework for estimating biomass indices from South African demersal trawl survey data (1985-2016), with an initial focus on priority trawl by-catch species as identified by a Demersal Scientific Working Group task team. This document extends the initial analysis by Winker et al. (2017) to compare results produced by the geostatistical delta-GLMM with design-based survey biomass estimates for hakes through 2017 as used in the South African hake 2017 reference case assessment (Rademeyer and Butterworth 2017). The specific purpose is to provide further research towards addressing the

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question: Should model-based geostatistical trawl abundance indices be considered in hake assessments as alternative to the current design-based estimator?

Materials and Methods
The data included in this analysis comprised density estimates (kg per nm² area swept) from demersal research trawl surveys conducted during summer and winter along the West Coast (1985-2017) and during autumn and spring along the South Coast (1986-2016) by the Fisheries Branch of DAFF. For the purpose of comparability, we used the subset of data that corresponds to the specifications of the South African hake 2017 reference case assessment (Rademeyer and Butterworth 2016), and therefore excluded all stations at locations deeper than 500m from the analysis. As part of the data preparation for the Geostatistical delta-GLMM, we proceed by using a 2.5’ × 2.5’ grid that encompasses the spatial domain of the 0-500m depth range for both South African coasts (Thorson et al. 2016). Based on this grid, each coast was then objectively divided into 250 polygons following the k-means described in Thorson et al. (2015).

The design-based abundance estimates were calculated using the current approach as described in Winker et al 2017, who also provide an overview and general description of previous geostatistical delta-GLMM applications to South African demersal trawl survey data. For a full documentation of the geostatistical delta-GLMM, we refer to the work by Thorson et al. (2015). In addition, Thorson et al. (2016) presents an application to South African West and South Coast trawl survey. A corresponding worked example for jacopever Helicolenus dactylopterus based on the South African West Coast survey catch rates, is publicly available on GitHub (https://github.com/nwfsc-assess/geostatistical_delta-GLMM).

The design-based and new model-based biomass indices are compared in terms of point estimates, normalized trends, observation variance (CV) and relative errors between point estimates for shallow-water hake M. capensis and deep-water hake M. paradoxus along the West- and South Coast of South Africa.

Results and Discussion
The results suggest that both the biomass indices for M. capensis from the West- and South Coast M. paradoxus from the West-Coast are comparable in terms of point estimates (Figs. 1) and relative abundance trends (Fig. 2). By contrast, the model-based biomass estimates for
South Coast *M. paradoxus* were notably larger than the design-based biomass estimates (Fig. 1d), which also resulted in some notable differences between the relative abundance trends (Fig. 2d). Relative error plots, also denoted MSRE values (Fig. 3) confirmed that the two alternative biomass indices for *M. capensis* were most similar, which further contrasted the relatively poor agreement between the South Coast *M. paradoxus* biomass indices (Fig. 3). The Geostatistical delta-GLMM produced overall more precise estimates for West- and South Coast biomass estimates of *M. capensis* and West Coast estimates of *M. paradoxus*, as judged by on average smaller CVs, whereas *M. paradoxus* South Coast biomass CVs were substantially inflated relative to the design-based estimates (Table 1).

The observed differences between the design-based and geostatistical model-based results are likely related to differences in spatial the distribution of the two species. *M. capensis* is generally more evenly distributed across the continental shelves of both coasts (Figs. 4-5), and has consistently high encounter rates of even up to 100% along the South Coast in some years. In contrast to *M. capensis*, *M. paradoxus* exhibits a patchier distribution with high density areas typically located further offshore within deeper strata (Figs. 5-6). In particular, the predicted high density cells for the South Coast appear to be confined to areas along the continental shelf (Fig. 6). We would therefore expect that *M. capensis* is less likely to violate the assumption that of a homogeneous distribution within a given stratum, which is crucial to design-based index estimation (Petitgas 2001). Geostatistical models, by contrast, are specifically designed to account for patchy distribution with distinct high and low density areas, and relies on the assumption of spatial dependency of population densities, with densities between nearby sites assumed to be more similar (spatially correlated) than densities between sites that are farther apart.

Further work should explore:

- Applying the geostatistical delta-GLMM to an extended grid to include grid cells and trawls that fall within the 500-1000m depth range (see Fairweather et al 2017)
- Applying the geostatistical delta-GLMM to combined seasonal surveys based on biannual time steps
- The effects of the differences in biomass estimates and associated uncertainty (CVs) in the form of robustness tests relative to the current South African hake reference case assessment (Rademeyer and Butterworth 2017)
References
Fairweather, T.P., Durholtz, D., Winker, H. 2017 How best might we take results from the extension of surveys into deeper water into account? MARAM/IWS/2017/Hake/P8.

Table 1. Means and standard deviations (sd) of estimated annual observation error CVs from the current design-based estimator and the geostatistical delta-GLMM estimator, summarized by species and seasonal west coast and south surveys.

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Fig. 1. Comparison of estimated indices of abundance (Biomass in tons) using the design-based estimator (DB) and the geostatistical delta-GLMM (GEO) for *M. capensis* along the (a) West Coast and (b) South Coast; and *M. paradoxus* along the (c) West Coast and (d) South Coast. Error bars denote the approximated with 95% intervals and dashed lines represent loess smoothers fitted to each index as a means to illustrate the underlying trends. Solid symbols are for the surveys conducted by the RV Africana with the old gear and open symbols with the new gear, while grey filled symbols are for the surveys conducted using a commercial vessel (by the FV Andromeda in 2013 - 2015; and in 2016 by the FV Compass Challenger in 2016) with the new gear.
Fig. 2. Comparison of normalized indices of abundance based on the design-based estimator (DB) and the geostatistical delta-GLMM (GEO) for *M. capensis* along the (a) West Coast and (b) South Coast; and *M. paradoxus* along the (c) West Coast and (d) South Coast. Error bars denote the approximated with 95% intervals and dashed lines represent loess smoothers fitted to each index as a means to illustrate the underlying trends. Solid symbols are for the surveys conducted by the RV Africana with the old gear and open symbols with the new gear, while grey filled symbols are for the surveys conducted using a commercial vessel (by the FV Andromeda in 2013 - 2015; and in 2016 by the FV Compass Challenger in 2016) with the new gear.
Fig. 3. Relative errors between the geostatistical biomass estimates (GEO) and the design-based biomass estimates (DB) for *M. capensis* along the (a) West Coast and (b) South Coast; and *M. paradoxus* along the (c) West Coast and (d) South Coast. Red lines represent loess smoothers fitted to relative errors to superimpose the annual trends.
Fig. 4. Map showing spatiotemporal density estimates from West Coast summer surveys for *Merluccius capensis* produced using the geostatistical delta-GLMM.
Fig. 5. Maps showing spatiotemporal density estimates from South Coast summer surveys for *Merluccius capensis* produced using the geostatistical delta-GLMM.
Fig. 6. Maps showing spatiotemporal density estimates from West Coast summer surveys for *Merluccius paradoxus* produced using the geostatistical delta-GLMM.
Fig. 7. Maps showing spatiotemporal density estimates from South Coast summer surveys for *Merluccius paradoxus* produced using the geostatistical delta-GLMM.
Appendix A

Table A1: Geostatistical abundance estimates and associated CVs in thousand tons for *M. capensis* for the depth range 0-500m for the West Coast (WC) and South Coast (SC). Values in bold are for the surveys conducted by RV Africana with the new gear, while underlined values are for the surveys conducted by the commercial vessel (FV Andromeda in 2013-2015; and in 2016 by the FV Compass Challenger in 2016) with the new gear.

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Table A2: Design-based abundance estimates and associated CVs in thousand tons for *M. capensis* for the depth range 0-500m for the West Coast (WC) and South Coast (SC). Values in bold are for the surveys conducted by RV Africana with the new gear, while underlined values are for the surveys conducted by the commercial vessel (FV Andromeda in 2013-2015; and in 2016 by the FV Compass Challenger in 2016) with the new gear.

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**Table A3:** Geostatistical abundance estimates and associated CVs in thousand tons for *M. paradoxus* for the depth range 0-500m for the West Coast (WC) and South Coast (SC). Values in bold are for the surveys conducted by RV Africana with the new gear, while underlined values are for the surveys conducted by the commercial vessel (FV Andromeda in 2013-2015; and in 2016 by the FV Compass Challenger in 2016) with the new gear.

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### Table A4: Design-based abundance estimates and associated CVs in thousand tons for *M. paradoxus* for the depth range 0-500m for the West Coast (WC) and South Coast (SC). Values in bold are for the surveys conducted by RV Africana with the new gear, while underlined values are for the surveys conducted by the commercial vessel (FV Andromeda in 2013-2015; and in 2016 by the FV Compass Challenger in 2016) with the new gear.

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