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Northwest Atlantic Fisheries Organization

Serial No. N6340 **NAFO SCR Doc. 14/043**

SCIENTIFIC COUNCIL MEETING – JUNE 2014

A Bayesian Approach to the Assessment of West Greenland Halibut: Rationale and Critique.

By

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ABSTRACT.

A *Bayesian/MCMC* approach with the modified Logistic equation incorporating a term which integrates either the constant for the natural logarithm (2.71828) and normally distributed random numbers (e^{v}) or the variability of the Sea Surface Temperature (SST_{SD}, lagged 6 years) with auto-correlated residuals is implemented. The *SST* was sampled from the area of West Greenland Halibut (*WGH*) juvenile (age class 1) drift in the mixing layer (which is proposed as a system-wide co-driver).

The evaluation of both sub-exploitation and overfishing shifts in relation to the cut lines for B_{MSY}: 0.3 (unrealistic), zero or the mean from the standardized series (highly precautionary) or (local) linear equilibrium values (relatively useful) and the stock appears to be over-exploited (even assuming the linear fit) during 2012-11 and close to equilibrium values during years 2006-2009.

It is suggested that the Bayesian framework may be useful, provided that the population model that underlies the simulations has the sufficient degree of resolution to describe the complex dynamics which may drive both recruitment and abundance in *WGH*.

While the incorporation of the environmental forcing results in a forecasted biomass series that approximates non-linear approaches developed by the author, estimates and reference points are considered rough proxies (of proxies) and the method does neither show the resolution nor the capacity to explain the (highly non-linear) mechanics behind the data. The correlation between both of the simulated outcomes is significant ($p<0.05$). The Bayesian/Logistic approach is unable to discriminate between results from either random or auto-correlated residuals with a clear memory effect in the series (common in such dynamical systems). The (between years) variability is "crunched down" by the method which approximates series of means with no dispersion (linear methods may be inappropriate to address the variability in the signal).

This implies several shortcomings which may be critical to achieve both short and medium term management plans as well as sustainability and conservation: it may lead to assessment errors as the stock may be both underestimated at high abundances (leads to sub-exploitation) and -what is most important- overestimated at relatively low numbers (leads to systematic overfishing when the stock is as most vulnerable): this mechanism is regarded as a co-factor contributing to the reduction of mean size in halibut populations as the effects of overfishing may have the highest impact as the stock is overestimated in the relatively lower abundances.

The critique herein is expressed on basis of the grounds of population processes seen as non-linear dynamical systems, resulting from the interaction between both abiotic and biotic factors, showing strong dependencies to external forcing, lags and cycles or pseudo-cycles.

Several concepts such as constant and dynamic reference points, differential intrinsic rate of increase, variable carrying capacity, environmental forcing and differential effects of fishing mortality, among others, are discussed in order to propose improvements for the assessment and modeling of the *WGH* dynamics.

Key words: Bayesian, logistic equation, West Greenland Halibut, variability, modeling, assessment, sub-exploitation, overfishing, sustainability, conservation.

INTRODUCTION.

Currently, linear approaches -such as the *Bayesian Markov Chain Monte Carlo* (*Bayesian/MCMC*, also called herein "*Bayesian runs*" and *"Bayesian-Logistic"* approach) methods in combination with the Logistic equation (or some derivative) are being used for fisheries assessment. Some of the fundamental assumptions of this probabilistic framework are that (a) population processes (such as recruitment and the temporal evolution of biomass) are the result of random processes, (b) neither environmental forcing (correlations with external variables) nor memories (longer than a year) or lags are taken into account and –among other factors- (c) residuals are expected to be random. Also, *Bayesian runs* are carried out on abundance, catches and Catch Per Unit Effort (*CPUE*) series in which no variability in the data is analyzed: the signals (which are to be approximated) consist of mean values which may give some rough indications of trends. Nevertheless, the lack of the main part of the information in the signal (which lies in the variability of the data) is omitted. Further details on the background for *Bayesian runs* are beyond the scope of this paper and may be found elsewhere in the literature (for reviews, see McAllister and Kirkwood. 1998; Andre and Hilborn, 2001 and Meyer and Millar, 1999, among others).

There is a large body of evidence in fish stock dynamics indicating several deterministic aspects: environmental forcing, dependencies (correlations and possible feed-backs), as well as lags with external drivers for both density-independent and density-dependent processes, the combined and differential effects of fishing mortality under different external conditions and levels of numbers, the variable carrying capacity of the environment, variable natural mortality and differential rates of increase related to levels of abundance, densities and external conditions.

Currently, a working paper (Solari et al., 2014) shows that West Greenland Halibut (*WGH*) dynamics (abundance and Age class 1) may be related to (i) the variability of the Sea Surface Temperature (SST_{SD}) within the area of juvenile drift in the mixing layer, considering a lag of six years and (ii) recruitment to the population (at approximately age 6) and the fishable stock can be further estimated from age class 1, considering a lag of five years. Furthermore, recruitment, abundance (to the population and fishery) and *CPUE* are found to follow cyclic trajectories, i.e. forward (compensatory) and backwards bending (depensatory) trends at different levels of numbers. These processes show dependencies, lags and memories, are highly non-linear and the information from the signals is lost to a high degree if the analysis and modeling are based on a linear approximation method combined to the Logistic equation.

The aims of this study are to show the outcome of (i) a *Bayesian/MCMC* with a modified Logistic equation which incorporates either the lagged variability of the Sea Surface Temperature (SST_{SD}) or the constant for the natural logarithm (2.71828) and normally distributed random numbers (e^{v}) and (ii) a rationale and critique for such a method and proposals for improvements within the linear and non-linear frameworks. In the discussion section of this paper, I put forward some argumentation on why approximating series of mean values with *Bayesian runs* may lead both to the systematic underestimation of the halibut stock at high abundances (sub-exploitation) and –what is most critical- its over-estimation at low abundances (overfishing): this mechanism is considered one of the main co-factors in the reported reduction of mean size in halibut populations.

DATA, BAYESIAN RUNS AND RESULTS.

Data on abundance and total catches (in 10^3 Tn^3) on West Greenland (NAFO areas 0 and 1) after Jørgensen (2012) and GINR (2013) were used in this study (Fig. 1). Until the end of the development of the environmental forcing study referred in this study, no raw data was made available. We used both *WinBUGS* and *R* scripts to run the analysis and simulations.

For the Bayesian simulations, we used two models, namely:

Model 1.

$$\mathrm{B}(t+lag) = B[t] - \frac{H(t)}{K} + B[t]*r*(1 - B[t]*SSTSD[i]) \qquad \text{(Eq. 1)}$$

Model 2.

$$\mathrm{B}(t+1) = \left(B[t] - H(t) + \frac{B[t]*r}{K}\right)*\ e^{v} \qquad \text{(Eq. 2)}$$

where *B* is biomass, *H* is the harvest (or catches), *r* is the intrinsic rate of increase and *K* is the carrying capacity, being and SST_{SD} (in Eq. 1) the standard deviations or variability in the environmental series, considering a six years lag (which is the assumed time to recruitment to the population in *WGH*), *e* (in Eq. 2) the constant (2.71828, the base of the natural logarithm) and *v* a (normally distributed) random number (sampled for each iteration).

Unless otherwise stated, all the variables were log transformed (Log) and standardized (Z) both to meet the conditions for statistical normality and to facilitate visual comparison. The main results are presented in this section and complementary information on the simulations (Model 2) is given in Appendix I.

Fig. 1 shows the biomass (after Jørgensen, 2012) and catch (10^3 Tn^3, after Jørgensen and Treble, 2014) series. Catches are close to the linear equilibrium values. Mean (survey) values are used to recommend catch levels and the within area/year variability in the data (the signal) is omitted. From a non-linear viewpoint, this implies both that (a) the oscillations and variability of the data around mean values (the signal of highest value) are poorly understood and the stock appears to be both overestimated and overfished at the lower abundances and (b) there is an underestimation of the stock at the relatively higher abundances, periods in which fishing mortality could be higher.

Fig. 2 a. shows the relationship between the Catches/F_{MSY} ratio (lagged 6 years) and the variation of the *SST*. Similar levels of fishing mortality are maintained without consideration of neither the positive nor negative slopes in the pulses of the environmental co-driver. Also, there is a 3-year-pattern in fishing mortality which is adapted to the needs of the commercial fleet rather than to the oscillations in abundance (a co-factor in overfishing during depensatory population growth phases in relatively).

Fig. 2 b. depicts the Sea Surface Temperature variation (SST_{SD}, ^{o}C, continuous line), after IGOSS (2013) for the halibut juvenile pelagic drift area within Lat. 62.5-64.5ºN and Long. 55.5-57.5ºW and Abundance Index series (lagged 6 years) from 1997-2011 (N=15), interpolated by a cubic spline (dashed line). It is suggested that recruitment (at age class 6) and abundance in *WGH* may respond as the inverse to *SST* variations around the mean ($p< 0.05$) within the pelagic drift area. Floor and ceiling values in abundance are expected as the inverses of the external forcing, considering the same lag. The positive and negative trends, slopes and amplitudes determined by the peak values may be useful to propose a (non-linear) range of sustainable catches adjusted to the variable carrying capacity of the environment.

Fig. 3 shows the phase plane of Biomass (B/B_{MSY}) and fishing mortality (Catches/F_{MSY}) resulting from a *Bayesian/MCMC* run ($8*10^5$ iterations, Eq. 1) incorporating the variability of the *SST* (SST_{SD}, lagged 6 years) from the area of drift in the mixing layer of Age class 1 halibuts. The evaluations of both under-exploitation and overfishing shift in relation to the chosen cut lines for B_{MSY}: 0.3 (dashed straight line; unrealistic), zero (or mean of the standardized variable) or overall and local linear fits (relatively useful but still being rough proxies). Non-linear approaches will allow to finely adjust fishing mortality and exploit the stock in a sustainable strategy as function of both the combined effects from the external forcing and past fishing mortality. Also, within a linear framework, it is proposed that estimations around equilibrium values may be useful -relative to the 30 or 50% cut lines- to manage the fisheries and assuming such a framework, a clear overfishing has occurred during years 2010-2011.

Fig. 4 depicts the Biomass (B/B_{MSY}) and fishing mortality (F/F_{MSY}) series resulting from a *Bayesian/MCMC* run ($8*10^5$ iterations) incorporating the variability of the *SST* (lagged 6 years) in the area of drift in the mixing layer of Age class 1 halibuts (Eq. 1). The estimated biomass values are indicated by the (dashed lines) square.

Fig. 5 depicts the relationship between Abundance and Catches (years 1997-2012) fitted by a cubic spline (dashed line) and a distance-weighted least squares (non-linear, continuous line) indicating two possible cycles at two different levels of abundance.

Fig. 6 shows the phase plane of the observed Biomass (continuous line) and simulated median (dashed line). The oscillation in the simulated data is within the range of the cycles (levels of abundance) –assumed to be– determined by the combined effects from both the environmental forcing and fishing mortality.

Fig. 7 depicts the F/B_{MSY} from two *Bayesian runs* with the modified Logistic equation incorporating a term (e^{v}) which integrates the constant for the natural logarithm (2.71828) and normally distributed random numbers which may resemble noise (Eq. 2) and the variability of the temperature (SST_{SD}) with auto-correlated residuals (Eq. 1). The correlation between both of the simulated outcomes is significant ($p<0.05$). The Bayesian approach is unable to discriminate between local trends resulting from either random or auto-correlated residuals with clear memory effect (dependency on preceding values; common in such dynamical systems) in the series. The (between years) variability is "crunched down" by the method, a shortcoming which may be critical to find the mechanics behind the data and it may lead to assessment errors as the stock is both underestimated at high abundances (leads to under-exploitation) and overestimated at relatively low numbers (leads to overfishing). Further, Fig. 7b depicts four examples of signals (SST variability with auto-correlated residuals and three cases, Sample 1-3, of random numbers sub-sampled from the iteration) which affect the Logistic equation in the Bayesian runs. Signal influence is "crunched down" to highly correlated series of medians (rough proxies), a mechanism which will lead to underestimation of the stock at high abundances (sub-exploitation) and overestimation at the lower abundances (which will lead to overfishing).

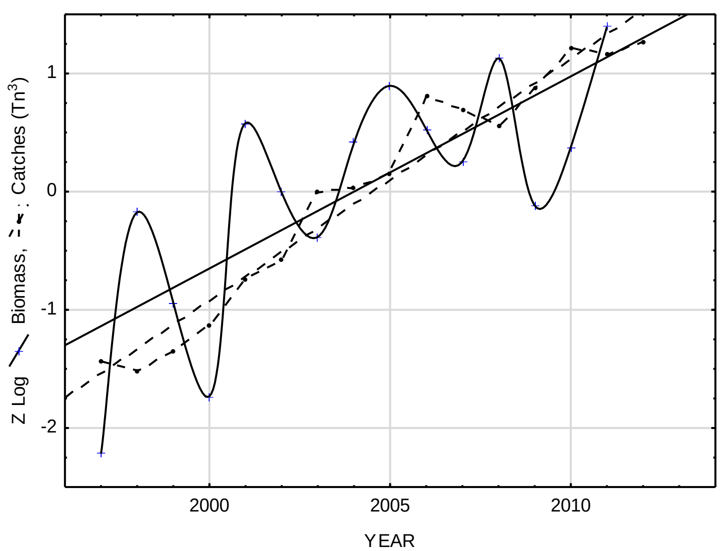

Figure 1. The log transformed (Log) and standardized (Z) biomass (after Jørgensen, 2012) and catches (10^3 Tn^3, after Jørgensen and Treble, 2014).

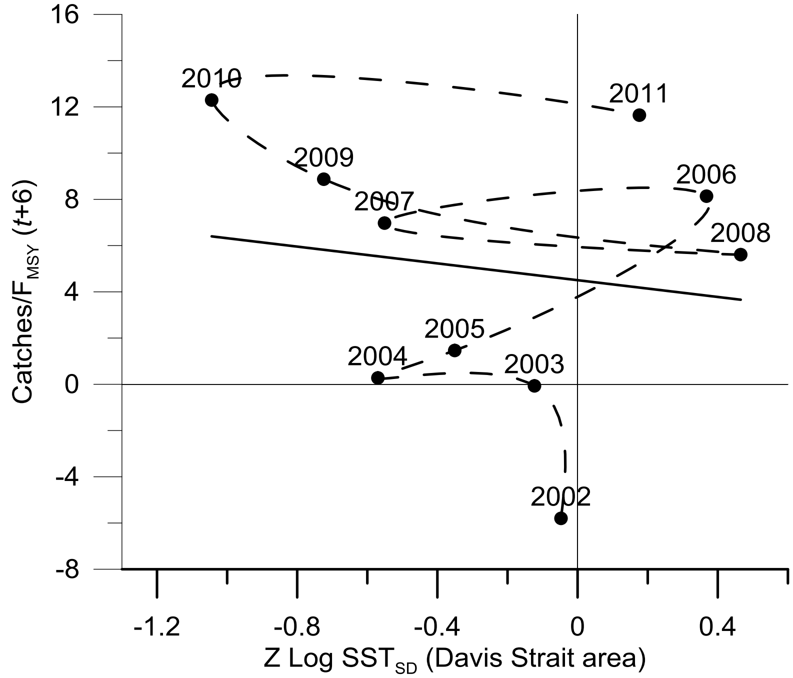

Figure 2 a. Ratio Catches/F_{MSY} (lagged 6 years) and the variation of the SST_{SD}. Similar levels of fishing mortality are maintained without consideration of the pulses in the environmental co-driver. Similar levels of fishing mortality are maintained without consideration of neither the positive nor negative slopes in the pulses of the environmental co-driver.

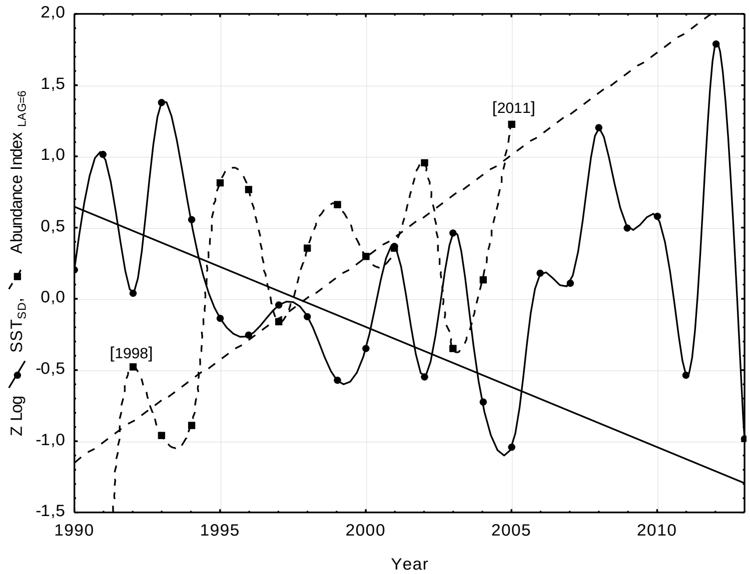

Figure 2 b. The standardized (Z) log transformed (Log) Sea Surface Temperature variation (*SST_{SD}*, ^{o}C, continuous line), after IGOSS (2013) for the halibut juvenile pelagic drift area within Lat. 62.5-64.5^{o}N and Long. 55.5-57.5^{o}W and Abundance Index series (lagged 6 years) from 1997-2011 (N=15), interpolated by a cubic spline (dashed line). It is suggested that recruitment (at age class 6) and abundance in *WGH* may respond as the inverse to *SST* variations around the mean ($p< 0.05$) within the pelagic drift area. Floor and ceiling values in abundance are expected as the inverses of the external forcing. The positive and negative trends and amplitudes determined by the peak values may be useful to propose a (non-linear) range of sustainable catches adapted to the variable carrying capacity of the environment (from working paper).

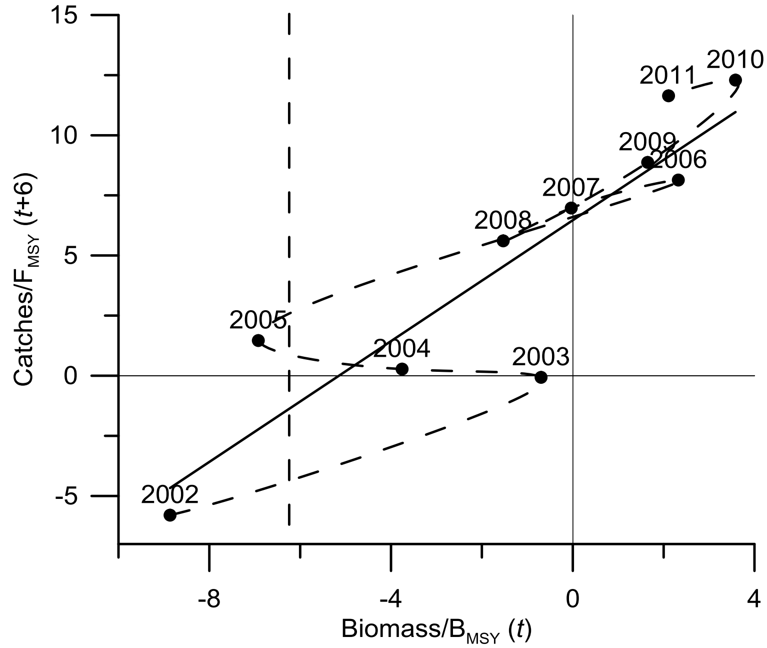

Figure 3. The phase plane of Biomass (B/B_{MSY}) and fishing mortality (Catches/F_{MSY}) resulting from a *Bayesian/MCMC* run ($8*10^5$ iterations) incorporating the variability of the *SST* (SST_{SD}, lagged 6 years) from the area of drift in the mixing layer of Age class 1 halibuts (Eq. 1). Evaluation of both under exploitation and overfishing shifts in relation to the cut lines for B_{MSY}: 0.3 (dashed straight line; unrealistic), zero or linear fit. It is proposed that estimations around the linear equilibrium values may be useful to manage the fisheries from such linear criteria. However, a clear overfishing may have occurred during years 2010-2011.

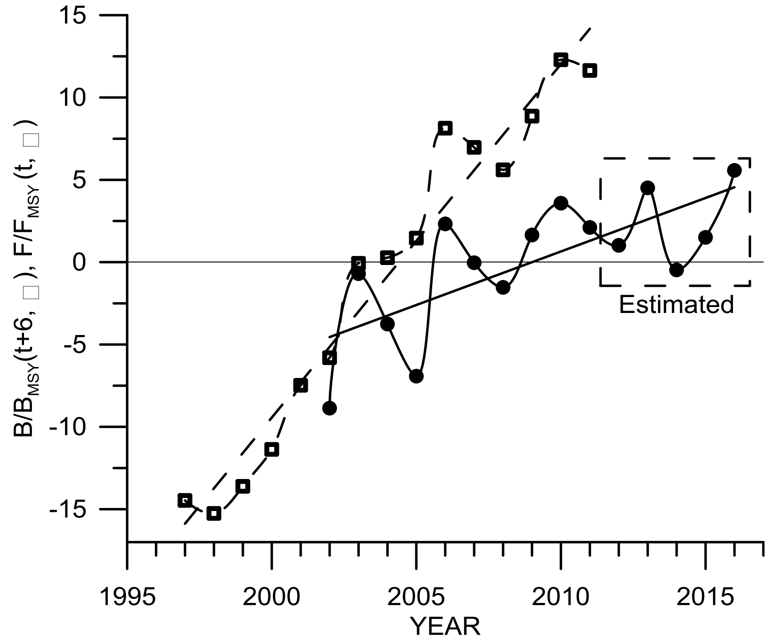

Figure 4. The Biomass (B/B_{MSY}) and fishing mortality (F/F_{MSY}) series resulting from a *Bayesian/MCMC* run ($8*10^5$ iterations) incorporating the variability of the *SST* (lagged 6 years) in the area of drift in the mixing layer of Age class 1 halibuts (Model 1, Lag=6). The estimated biomass values are indicated by the squared with dashed lines.

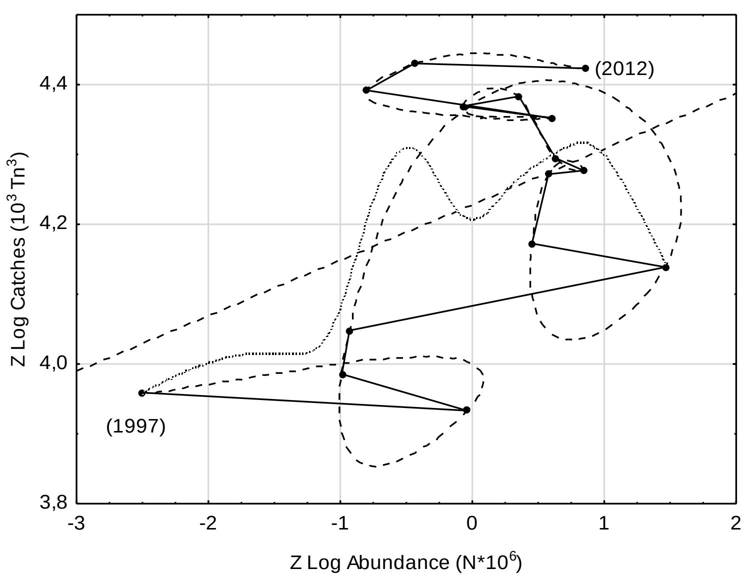

Figure 5. The relationship between Abundance and Catches (years 1997-2012) fitted by a cubic spline (dashed) and a distance-weighted least squares (non-linear, continuous line) indicating two possible cycles at two different levels of abundance.

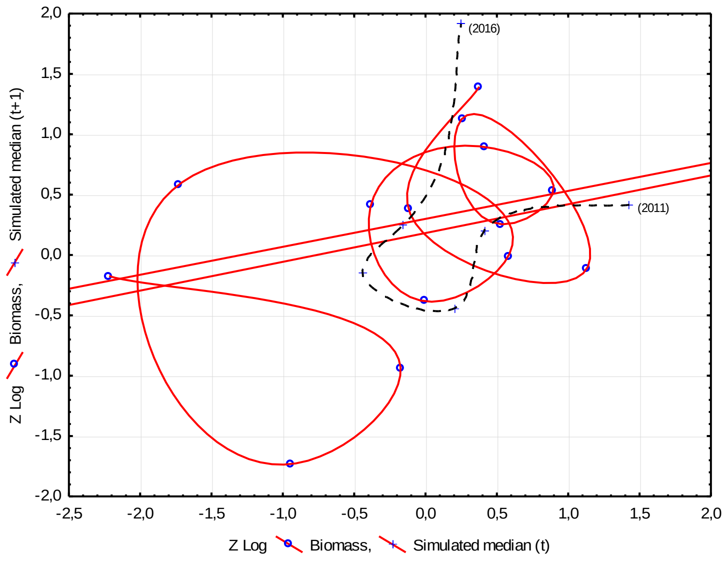

Figure 6. The phase plane on the log transformed (Log), standardized (Z) observed Biomass (continuous line) and simulated median (dashed line). The oscillation in the simulated data is within the range of the cycles (levels of abundance) –assumed to be- determined by the combined effects from the environmental forcing and fishing mortality.

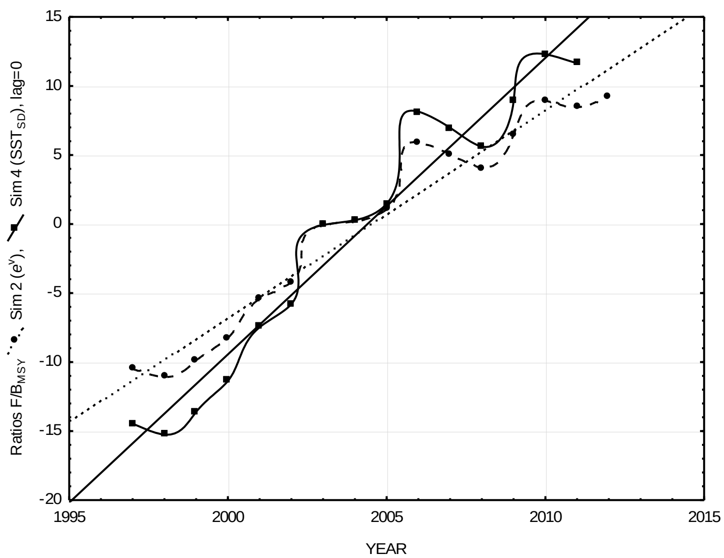

Figure 7a. The F/B_{MSY} from two *Bayesian runs* with the modified Logistic equation incorporating a term (e^{v}) which integrates the constant for the natural logarithm (2.71828) normally distributed random numbers (Eq. 2) and the variability of temperature (SST_{SD}) with auto-correlated residuals (Eq. 1). The correlation between both of the simulated outcomes is significant ($p<0.05$). The Bayesian-Logistic approach is unable to discriminate between local trends resulting from either random or auto-correlated residuals with clear memory effect (dependency on preceding values; common in such dynamical population systems) in the series. The variability is "crunched down" by the method. This shows a shortcoming which may be critical to find the mechanics behind the data and it may lead to assessment errors as the stock is both underestimated at high abundances (leads to under-exploitation) and overestimated at relatively low numbers (leads to overfishing).

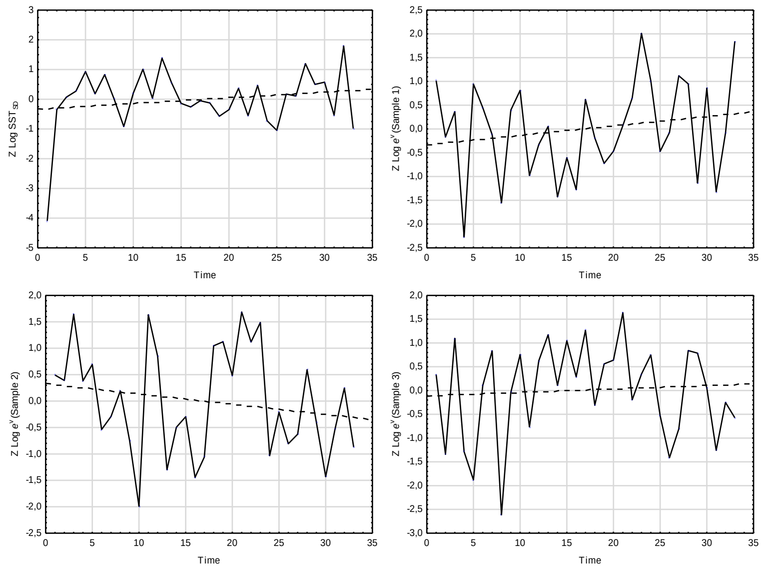

Figure 7b. Four examples of signals (SST variability with auto-correlated residuals and three cases, Sample 1-3, of random numbers sub-sampled from the iteration) which affect the Logistic equation in the Bayesian runs. Signal influence is "crunched down" to highly correlated series of medians which will lead to underestimation of the stock at high abundances and overestimation at the lower abundances (which will lead to overfishing).

DISCUSSION.

<u>Rationale and critique.</u>

WGH is a key species for food safety, the livelihood of the fishermen communities and the economy of Greenland, as well. As researchers, our mission is to improve and deliver a scientifically based assessment and the frameworks and tools to achieve the sustainable exploitation and conservation of the stocks.

This critique is expressed on basis of both (i) the grounds of population processes seen as non-linear dynamical systems, resulting from the interaction between both abiotic and biotic factors combined to the variable carrying capacity of the environment and differential effects of fishing mortality. Such systems show strong dependencies to the external forcing, lags and periodicities which are driven both by density-dependence and the environment; (ii) the aim to improve both the assessment and modeling on *WGH* in order to optimize the exploitation of the stock, attaining sustainability and conservation.

The *pioneers* in fishery science, at the end of the 18th century (the so called "*observational oceanographers*") and the first papers published at the International Council for the Exploration of the Seas (ICES), during the beginning of the 1900's, related both recruitment and abundance in marine fish, birds and mammals to cycles in the environment (Petersen, 1896; Hjort, 1914; Hjort, 1926; Iselin, 1938; Russell, 1939; Iselin, 1940; Rollefsen, 1948). The historical perspective on the environmental forcing as a co-driver and the original descriptions by the oceanographers from a century ago are key factors for the understanding of the mechanics behind the data. Furthermore, there is an increasing body of evidence showing both that recruitment (to the population, area and fishery) and the temporal evolution of abundance may be the result of deterministic, density-dependent and density-independent population processes which are both affected by the combined effects from the environmental forcing and levels of exploitation at several discrete levels of abundance. The volume of scientific literature on populations as dynamical systems and the multi-oscillatory nature of the environmental forcing is voluminous and I have chosen to refer to a few of our own studies such as Solari et al. 1997, 2003, 2008, 2010; Bas et al., 1999; Solari, 2008, 2010, 2011, 2012; Ganzedo et al., 2009 and those by Sharp et al., 1983, 2003).

Assessment based on series of mean values.

Currently, the *WGH* assessment is carried out on series of mean values (a basic descriptive statistic resulting in highly rough proxies) from the surveys: the variability in the data, maxima, minima, outliers, signal-to-noise-ratio (which may be density-dependent), missing values (which may show the absence of a species due to impacts of different nature) and environmental forcing (a knowledge which will allow us to finely adjust fishing mortality and propose short and medium term sustainable strategies), among other factors, are omitted from the analysis. The (non-linear) signal is stripped-down to a level (yearly mean values) which hardly can reflect the main information on the (density-dependent and density-independent) population processes. Also, it can be misleading, as the variability in the external forcing (which is the case for *WGH* offshore) may show significantly different trends from the series of means and local trends in maxima and minima may (do) differ. Variability in the population series may depend both on the density dependent processes and differential responses to a set of external combined effects (such as from environmental pulses combined to the levels of fishing mortality, during the positive and negative growth phases of a cycle or period of some frequency). Also, we may be dealing with population processes consisting of multi-oscillatory/multi-frequency signals, that is, population responses to external pulses of different frequencies. Furthermore, linear approximations to the series of means will solely replicate the aforementioned shortcomings as the main (non-linear) signal on the population process (which reflects critical dynamical features) is taken out.

Moreover, working (solely) on series of means may have highly negative consequences on the assessment and management of the *WGH* stocks: (i) It sets the grounds for the underestimation of the stock at high abundances (which leads to a sub-exploitation) and the overestimation of population numbers at the lower abundances (which leads to overfishing). (ii) It implies that recommended TAC's will be below (for the higher abundances, i.e. abundances above equilibrium values) and above the sustainable ranges of exploitation (for the lower abundances, i.e. abundances below equilibrium values), adjusted to the variable carrying capacity of the environment, hence fishing less than possible during years with relatively higher recruitment to the population/area and fishery (compensatory phases) whereas a significantly higher fishing mortality will occur during the negative growth (depensatory) phases. (iii) Sustainable strategies and conservation require the analysis and modeling of the non-linear signals whereas series of means and approximations through different (linear) methods -as currently applied- imply that such critical aims become impossible to achieve. Fig. 8 and 9 show an schematic overview on these mechanisms.

Fig. 10 depicts the *WGH* frequency classes (in per cent of total catches) from the long-line fishery in Disko Bay (after Nygaard, 2014). . The dramatic shift in the demographic structure of the local stock (reduction of circa 10 cm within a 20 years period) can be attributed to the overestimation of the population at the lower abundances (assessment based on series of mean values where the variability in the data has been omitted from the analysis), the lack of non-linear models to which fisheries mortality can be finely adjusted and the combined effects from both environmental forcing and differential effects of the fishing mortality. Juvenile mortality (as a by-catch) from the shrimp fishery (which still remains to be addressed) may even contribute to demographic changes in the structure of the local stock. Although a source of error may be attributed to the tendency of the long-line to catch smaller individuals, the size of the samples comply above any requirements for statistical conditions and the shift reflected by the data is gradual and clear.

A successful assessment on *WGH* oriented both to sustainability and conservation should be based on the scientific method, proposal and testing for null hypothesis and carry out a full analysis of the data matrix using the wealth of linear and non-linear methods in order to uncover the highest possible knowledge on the population processes and environmental forcing in question.

The Bayesian-Logistic framework.

The (Gibbs sampler and) Bayesian framework may be useful, provided that the population model that underlies the simulations has the sufficient degree of resolution to describe the complex dynamics we address: estimates and reference points derived from the *Bayesian/MCMC-Logistic* approach result in rough estimates (i.e. "proxies-of-proxies") and the method does neither incorporate key factors nor shows the capacity to explain the mechanics behind the data or allows to propose a short or medium term exploitation strategy for conservation as the signal is crunched and causes for population processes remain unknown.

In general, the Logistic equation (or any derivative) is used to fit the outcome of the simulations while it may solely explain between 0.2-0.3 of the (between years) mean (or median) values in the series: no temporal evolution is considered for which trends in maxima and minima, strong correlations, memories, auto-correlated residuals and lags (common in such dynamical systems) remain ignored.

The resolution of the *Bayesian-Logistic* method becomes further critical as it is the aggregated data (mean values with a highly reduced signal) which is presented in the stock assessment reports. No variability analysis (on ceilings, floors, local slopes, outliers and missing values, among other features) is considered and the "crunching" of the signal incapacitates the assessment to finely adjust fishing mortality to the relatively high and -most importantly- the lower abundances.

Further, it is omitted that means and variability may show different trends (which is the case for the relationships in *WGH* abundance and the environmental forcing). Means (or medians) should be linked to the local (positive and negative growth) trends and the within- and between- year/s variability in the data: this may reflect in a higher degree the spatio-temporal evolution of the process and associated relationships, as well. The variability in the data is the part of the signals which reflect the features of highest weight in such population processes for which it should be incorporated into both the analysis and modeling of the *WGH* dynamics.

The issue of priors is critical, as well. Criteria for selecting priors are subjective: different authors chose parameters without any scientific evidence - in a "best-guess" pattern. Priors are often chosen on an arbitrary basis which may not be related to the signal reflecting the population process. This is an artifact of the probabilistic approach as variables which may be strongly correlated to the population process and be a relatively safe ground for the estimations are still ignored. Priors should be chosen both for maxima and minima in relation to the effect of key (system-wide) environmental factors and differential effects of fishing mortality.

If we assume that a probabilistic, linear approach combined to the Logistic equation can be used to describe a population system, then we should be able to find a convergence of results as compared to non-linear approaches. If we aim to use linear methods to analyze and model *WGH* dynamics, it may be mandatory to approximate the (non-linear) signals, as far as possible, in order to carry out a realistic fisheries assessment: this will enable us both to determine higher fishing mortality during periods of relatively higher abundances and adjust the fishing regimes to the lower abundances without any overestimation of the stock during periods of either low abundances or negative growth.

There are several further aspects which could be addressed to test for alternative models to describe the dynamics of *WGH*. A key question is how to describe –in a relatively simple and effective way- such complex systems without incurring in models with too many parameters or a multi-dimensionality which would be difficult to understand.

A linear (*Bayesian/MCMC*) approximation to a series of means (abundance from surveys, commercial catches and *CPUE*) becomes -in the assessment- a "*three proxy set*", one approximating the other (i.e. "a proxy (linear estimation) of a proxy (mean abundance series) of a proxy (signal in the raw data)". The maximum resolution in such an approach will go no further than a series of mean or median values. The signal in the series of observations is taken out and both reference points and estimations are rough or poor. Furthermore, it will make nearly impossible to propose short (3-4) and medium (5-10 years) term sustainable fishing strategies as the method considers a single year of memory whereas we know that the environmental forcing (system-wide variables) show longer dependencies or memory effects (i.e. strong correlations and dependencies on preceding values).

An advice based upon such "*proxies-of-proxies*" results contributes further to the underestimation of the stock at high abundances (i.e. sub-exploitation) and the overestimation of stock numbers at the lower abundances (which leads to overfishing). "Higher" and "lower" in this context are determined by values above and below (linear or non-linear) equilibria (i.e. as the stock is at a standstill, it neither grows positively or negatively). This may be one of the co-factors which explains the reduction in mean body length in halibut (and other) populations: the stock is overestimated for the lower population abundances and the overfishing which occurs acts as a selective force shifting the demographic structure towards the smaller sizes.

Moreover, the *Bayesian/MCMC-Logistic* approach will lead both to rough (or poor) reference points as it eliminates the non-linear signals (expected to be of different frequencies) from the data. which implies that it will make nearly impossible to propose short (3-4) and medium (5-10 years) term sustainable fishing strategies as the method, as well, considers a single year of memory (whereas we know that external forcing system-wide variables show longer dependencies on preceding values). Graphical representations of the described mechanism are depicted in Figs. 8 and 9. It is the variability in the data that will allow us to adjust fishing mortality to appropriate levels as the carrying capacity of the environment may vary.

A key question is whether the underestimation of the stock at high abundances (which leads to under exploitation, a higher fishing mortality is possible) may compensate for the overfishing which may occur as the stock is overestimated in the lower abundances: the answer can be negative as we have detected a shift or bias towards the smaller individuals during the last ten years. This has been reported at the NAFO meeting, 2014) for other stocks which are exploited using linear frameworks, as well.

<u>The Logistic equation</u> (and derivatives, such as the Schaefer production model): this approach –contrary to the scientific evidence in a wealth of publications where year class strength and abundance are related to environmental pulses- assumes that (i) r and K are constant and residuals are random and (ii) the population trajectory between zero and $K/2$ will be compensatory, independently of fishing mortality regime and density dependence (no Allé Effect or minimum viable population under which numbers and oscillations will tend either to a stand-still or zero). Further, neither lags nor memory effects or dependencies are assumed. The Logistic model has neither the sufficient degree of resolution nor the flexibility to describe such complex population systems and will explain less than (approximately) 25% of the variability in the data

<u>Uncertainty</u> may be an overused argument (due to the probabilistic nature of the approach) to "tag" estimations on a population process (recruitment, temporal evolution of abundance) which is assumed to be stochastic: there is still a serious doubt on whether uncertainty can be attributed either to randomness or it is

a parameter or a variable. However, there is evidence of both an environmental forcing (a co-factor determining year class strength and recruitment to the population and fishery) and auto-correlated residuals, common in (deterministic) population processes. We may -more realistically- assume that population signals may contain certain degrees of noise (or signal-to-noise ratio) which -in turn- may change as function of (i) age (series for juveniles appear to be more noisy than for other frequency classes), (ii) density dependence (relatively higher abundance cycles may show more outliers and a higher degree of noise) and (iii) density-independence (differential effects of the environmental forcing upon frequency classes and areas). The analysis of the signal-to-noise ratio (critical to finely estimate uncertainty determination of the fishable biomass and for short and medium term fisheries management plans) requires signal analysis to determine the level of possible white noise in the signal for different abundance cycles, frequency classes and environmental conditions.

Auto-correlated residuals are common in dynamical systems as population processes may respond to trends in environmental forcing and memory (arising from the interaction of the population with the environment) is a key feature determining such dependencies on preceding values.

Reference points (r, K and $K/2$, MSY, B_{MSY}, F_{MSY}) are key concepts and may have important consequences to fish stock analysis (estimation of recruitment and abundance), as well as management and conservation issues (recommended fishing mortality ranges, *TAC*'s, exploitation strategies, avoidance of recruitment overfishing, among other critical factors). These are based on the *Bayesian/MCMC* method linked to the Schaefer (1954) “Production –or *Maximum Sustainable Yield"* model which is a modification of the Logistic equation. While the constants (mainly r and K) may have a mathematical sense for the chosen model, the resulting description of temporal evolution of the population system is a highly rough proxy. A critical discussion on the reference points is suggested in order to improve both the assessment and modeling on the *WGH* and other exploited species, as well:

Intrinsic rate of increase (*r*). Within the logistic framework, it is both assumed that this parameter is constant and (what is critical) that a population will compensate no matter the exploitation regime and pulses from the environment. In this study, it is proposed that this parameter is not a constant but changes values within and between different cycles of abundance as a function of density-dependence: *r* is expected to change in both the compensatory and depensatory phases (at the zero and maximum slopes) of population growth and at inflection points (which are 6, 3 for a compensatory phase and 3 for a depensatory). Furthermore, there should be instantaneous values of *r*, as well, due to the ever changing environment and forward and backwards bending nature of the *CPUE*. However, the complexity of this issue should be reduced to a degree which we may handle both from the conceptual, computational and pragmatic viewpoints. For *WGH* modeling, we may come to consider, at least, two values of *r* in each trajectory or cycle, at different levels of numbers: one for the positive growth of the population and another for the depensatory or negative growth phase.

Carrying capacity (*K*). It is assumed that *K* is the maximum number of individuals in a population that can be sustained by the environment, indefinitely. The value of *K*, in classical fisheries assessments is drawn as a constant value over the years for which data exists. For instance, there may be over 50 years long series for which a constant value is determined around the minima and it is inferred that such "ceiling" is the *K* of the stock over the NAFO area/s. A single, constant value of *K* is misleading and has not the resolution to describe the ceiling or number of individuals that -for a certain area with particular environmental conditions- can be sustained. There is a large and increasing body of scientific evidence (since the end of the 1800´s) to the contrary and it is proposed that all population processes (such as growth, reproduction, recruitment, migration, availability of food items and other limiting resources in an ever changing environment) should be translated to a variable carrying capacity (K_t or K_i) which operates in each population cycle. This is one of the critical aspects of highest weight in modeling population dynamics and one of the key concepts to approach sustainability and conservation.

Maximum Sustainable Yield (*MSY*). This is another concept that should be discussed (and modified) as it -classically- is proposed as a constant or the maximum yield that can be harvested from a population, "*indefinitely*". Further, the *MSY* is considered a midpoint (or *K*/2) towards *K* (which is, again, a constant). This concept becomes critical as *K*/2 is overestimated for lower abundances (or negative growth/depensatory phases in the cycles) which will lead to overfishing during poor environmental conditions.

Natural mortality (*M*). This parameter -assumed to be constant in approaches linked to the Logistic equation- is associated to processes (predation, disease, cannibalism, competition among others) which are density-dependent and -hence- *M* should be addressed as variable. Also, there are genetic factors associated to *M* which may change as the structure of the population becomes biased (through fishing mortality) towards the smaller sizes (such as the case in *WGH*) in which higher population turn-over speeds may be expected. Furthermore, it is expected that this parameter may change as function of the variable carrying capacity of the environment.

Priors and non-dynamic reference points may be artifacts of the probabilistic framework linked to the Logistic model and -as I see it- they will ultimately be translated to assessments which will contribute to change the demographic structure of the population, overfishing and recruitment-overfishing. On the contrary, dynamic or differential reference points are needed for attaining sustainable exploitation strategies: these should be adjusted both to the positive and negative local growth trends and variable carrying capacity of the environment.

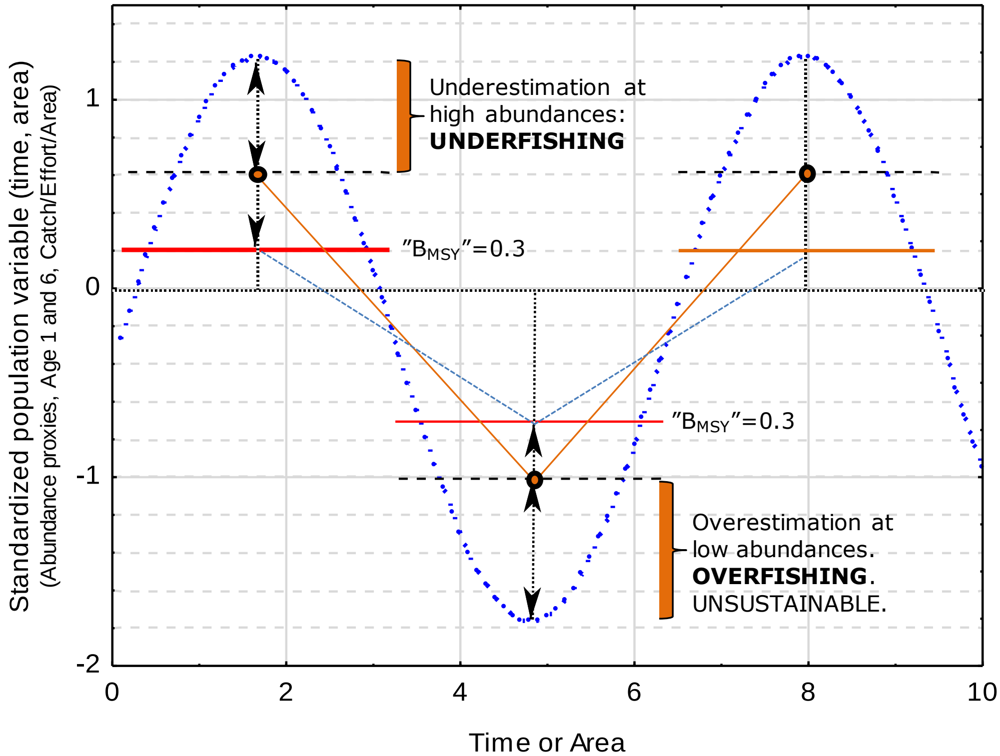

Figure 8. Consequences of eliminating the variability (main signal, auto-correlated residuals, outliers and noise) from the data for the analysis, assessment and quotas. As based on the processing of the data from the SAS scripts and assessment reports (*WGH* – and possibly other species/similar scripts). By the current assessment procedure, the system is reduced to the orange line and recommended quotas (blue dashed line): this results in under-fishing (at high abundances) and overfishing (at low abundances). Signal analysis is mandatory to gain knowledge on causal mechanisms and adjust catch ranges to a sustainable strategy where all parts can be satisfied.

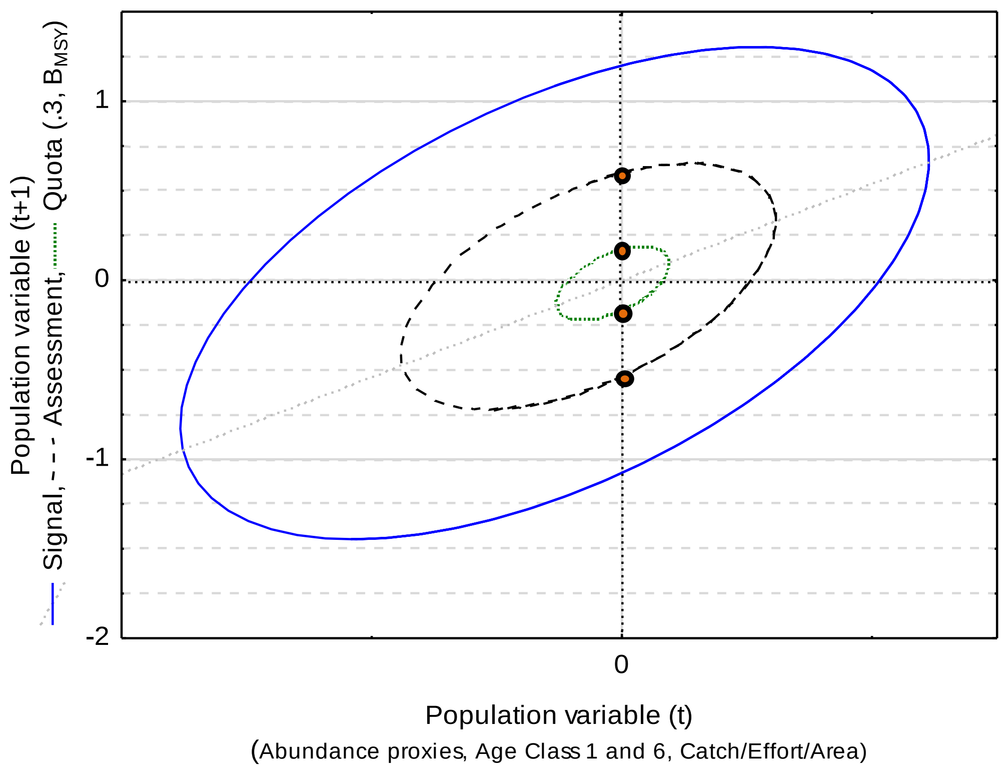

Figure 9. Example in the phase plane on how the system of signals shrink by eliminating all of the variability in the data (and determining two mean points and B_{MSY}=.3 thereby). Consequence is overestimation in low abundance (overfishing) and underestimation in high abundance (under fishing). Current assessment determines two points (orange dots, dashed trajectory) and recommends two further points (B_{MSY}= 0.3, inner trajectory). The signal, auto-correlated residuals, noise, environmental forcing, lags, dependencies, memory effects, feed-back mechanisms, and missing values are all ignored.

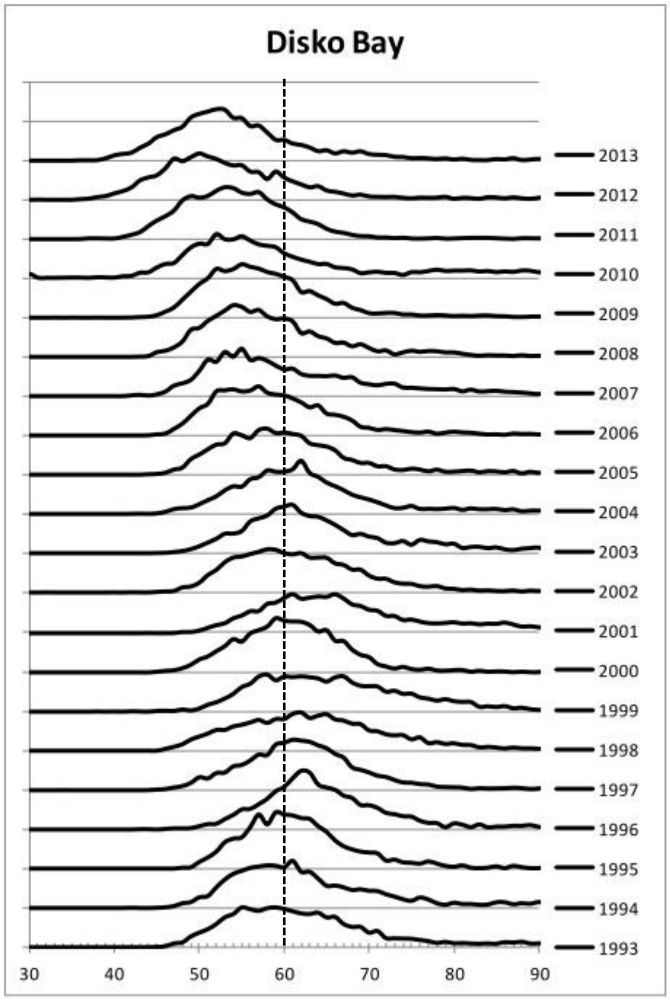

Figure 10. The *WGH* frequency classes (in per cent of total catches) from the long-line fishery in Disko Bay (after Nygaard, 2014). The dramatic shift in the demographic structure of the local stock (reduction of circa 10 cm within a 20 years period) can be attributed to the overestimation of the stock at the lower abundances (assessment based on series of mean values where the variability in the data has been omitted from the analysis), the lack of non-linear models to which fisheries mortality can be finely adjusted and the combined effects from both environmental forcing and fishing pressure.

Approaching sustainability and conservation.

At the Greenland Institute of Natural Resources (GINR), the combined shrimp-halibut surveys meet high international standards (infrastructure, manpower, know-how and sampling methods). A solid field work is a key factor for developing better assessment tools and the base for attaining both sustainability and conservation. However, it should be combined to a data analysis and modeling which take into account the signals which may reflect the environmental forcing and population processes under different fishing mortality levels.

Quantifying the contribution of compensatory and depensatory mechanisms, the environmental forcing and differential effects of fishing mortality in determining year class strength and population abundance are essential factors for assessing the spatio-temporal evolution of the stock and possible responses to exploitation strategies, variations in the carrying capacity of the environment and -eventually- climate change.

However, much remains to be known on the life history and dynamics of *WGH*. We deal with complex systems with interlinked features, lags, dependencies and delayed responses both to the combined effects from external pulses and fishing mortality during both compensation and depensation. Also, there may be possible feed-back mechanisms mediated through the positive and negative density-dependencies.

Although signal analysis and non-linear approaches can be more appropriate to model such systems, an effective linear approach should seek and describe further scientific evidences on both density-dependent and density-independent population processes, beyond the oversimplification derived from the assumption of populations processes being the result of random walks. Some of these aspects –to be incorporated into the modeling on *WGH* dynamics- are as follows, namely:

(i) System approaches using General Additive Models (GAM's) with both linear and non-linear functions (to describe variability, maxima and minima); (ii) System-wide environmental variables which may be proxies of the variable carrying capacity of the environment, $K_{(t)}$ or $K_{(i)}$.

(iii) Fishing mortality adjusted to $K_{(t)}$ and different, discrete levels of abundance (i.e. "orbits of stability"), differential values for the (dynamic) reference points, depending on whether abundance is under compensation or depensation.

(iv) Other factors such as: signal-to-noise ratio, outliers, zeroes, null and missing values, environmental forcing, optimal environmental values determining year class strength and abundance, spatial distribution, maxima and minima related to the conditions they arise, within year temporal and spatial variability, differential effects of fishing mortality, short-to-medium term management plans, environmental impact of trawling, by-catches of juvenile halibuts in the shrimp fishery, abundance of shrimp and polar cod, ice production, linkage of off-shore and in-shore systems, drift of age class 1, gonad development, among other factors.

(v) Otolith readings (through the Laser Ablation/Spectrometry method) to (through isotope determination) to estimate the timing for recruitment, age, migrations, foraging, speed of growth, a proxy of $K_{(t)}$, density dependence, memory effects, among other factors (on-going project).

(vi) Also, we aim to propose spatial exclusion areas (with null fishing mortality) in order to conserve the stock from recruitment overfishing and distribute fishing effort to correct -if possible- the demographic shift toward the smaller sizes detected under recent years.-

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Appendix I.

Commented *WinBUGS* runs.

Model 1.

#Formulae for the variables deriving from the *r* and *K* parameters

```
MSY <- (r*K/4);    BMSY <- K/2;    FMSY <- r/2
```

#Prior distributions of the parameters *r* and *K*

#Precision is related to the standard deviation (*sd*)

$sd * sd = \frac{1}{prec}$ es decir $prec = \frac{1}{sd*sd}$

```
r ~ dnorm(a, prec)
K ~ dunif(0,1)
```

#Values of *a* and *prec* are used for the prior distribution of *r*.

```
a ~ dgamma(0.05,0.1) ;   prec ~ dgamma(0.56,0.1)
```

#Biomass is estimated according to the model:

$$\mathrm{Biom}(t + lag) = ZLOG\_BIOM\_T0[t] - \frac{ZLOG_{CATCH_{T0}}}{K} + ZLOG\_BIOM\_T0[t] * r * (1 - ZLOG\_BIOM\_T0[t] * TEMP[i])$$

```
      for(i in 1:N) {
   BR[i+lag] <- B[i] - C[i]/K + B[i]  * r * (1 - B[i] * TEMP[i])
  }
}
```

Refrence points (Model 1 run),
Iterations: $80*10^3$

node	mean	sd	MC error	2.50%	5.00%	median	95.00%	97.50%
B_{MSY}	0.2501	0.1445	4.68E-04	0.0128	0.0253	0.2499	0.4749	0.4875
F_{MSY}	0.09923	40.12	0.1457	-2.0850	-1.0360	0.0472	2.5640	4.5540
K	0.5001	0.2889	9.36E-04	0.0255	0.0506	0.4998	0.9498	0.9749
MSY	0.04302	4.375	0.01589	-0.5118	-0.2654	0.0057	0.6042	1.1540
r	0.1985	80.24	0.2914	-4.1700	-2.0730	0.0944	5.1290	9.1080

Model 2.

```
model;
{
   MSY <- (r*K/4);     BMSY <- K/2;     FMSY <- r/2
```

Beyond *r* and *K*, v represents a measure of the error:

```
   r ~ dnorm(0.05, 0.5)I(0.05,0.5)
   K ~ dunif(0,1)
   v ~ dnorm(0, 1)
```

#Initial value of the simulated series:

BR[1]<- K

#Remaining values of the simulated series were computed as per:

```
           for(i in 1:N) {
```

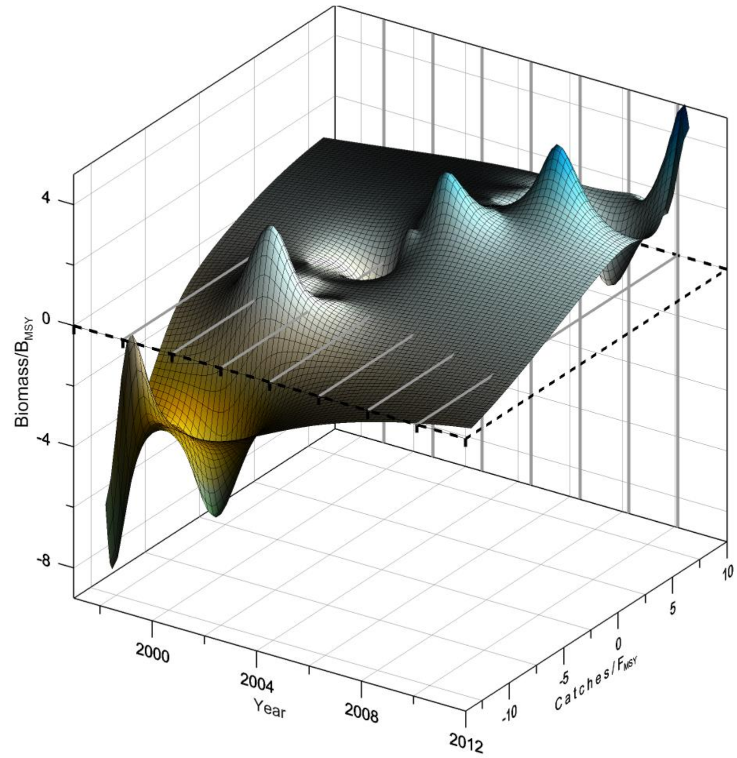
$$\text{Biom}(t+1) = \left(ZLOG\_BIOM\_T0[t] - ZLOG\_CATCH\_T0 + \frac{ZLOG\_BIOM\_T0[t] * r}{K}\right) * \; e^{v}$$

```
      BR[i+1] <- (B[i] - C[i]  + r  * B[i]/ K) * exp(v)
   }
}
```

Refrence points (Model 2 run), Iterations: $120*10^3$

node	mean	sd	MC error	0.025	0.05	median	0.95	0.975
B_{MSY}	0.2501	0.1443	3.99E-04	0.0127	0.02568	0.2494	0.475	0.4875
F_{MSY}	0.1366	0.06497	1.88E-04	0.03045	0.0361	0.1361	0.2386	0.2443
K	0.5001	0.2887	7.98E-04	0.02541	0.05136	0.4989	0.95	0.975
MSY	0.03412	0.02714	7.90E-05	0.00126	0.00249	0.02702	0.08884	0.09911
r	0.2733	0.1299	3.75E-04	0.06091	0.0722	0.2723	0.4773	0.4886
v	2.96E-04	1.002	0.00294	-1.965	-1.651	4.72E-04	1.651	1.958

End runs.



Overall B_{MSY}= in the range 0.5-0.6 (precautionary equilibrium values), even applied to local abundances both above (compensation or positive growth) and below (depensation, negative growth) is proposed as the starting biomass in order to adjust fishing mortality to the variable carryin capacity of the environment. B_{MSY} = 0.3 is unrealistic ans should be rejected.

End of file.