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Resource management under climate change: a risk-based strategy to develop climate-informed science advice

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ABSTRACT

Climate change is currently affecting the structure and function of Canadian aquatic ecosystems. Scientific advice on sustainable exploitation of biological resources (particularly fish stocks) does not usually take into account the potential impact of climate change on achievability of either near term (tactical) or long term (strategic) goals. We present a framework for conditioning scientific advice for sustainable fisheries to climate change. This framework recognises that all management of biological resources in the Department is implicitly or explicitly a form of risk management, thus the framework attempts to effect climate change conditioning in the decision risk profile. This approach contrasts a purely causal mechanistic based approach which considers climate change as a driver with known linkages to biological dynamics and produces estimates of stock size and production including the climate signal. Although our approach can also include specific mechanistic relationships linking climate and resource dynamics, it takes the extra step of quantifying the overall incremental risk in decision making on resource exploitation owing to climate change. In fact, this approach draws attention to the climate conditioned risk statements in the science advice rather than refinement of median prediction estimates of climate conditioned production as the most appropriate place to condition overall advice to climate change. It may be possible to develop a set of climate change conditioning factors given data and process-knowledge availability for a stock combined with a measure of the climate departures from baselines over the management period and resource sensitivity to climate change. These factors could be applied to particular cases based on general decision criteria in order to develop risk equivalent advice under climate change. This approach has partial analogs to the USA and Australia where risk equivalent buffers are applied to stock advice to account for uncertainty in data knowledge and technical basis for the assessment; thus, approaches of this nature have already proven to be operational in other jurisdictions.

1. INTRODUCTION

1.1 RATIONALE

Scientific advice for biological resource management in the Department of Fisheries and Oceans generally consists of evaluating the state of the resource, determining the impact of a human activity on the resource state and management outcomes, consistent with an implicit or explicit objective for resource state in the future. There is also an evaluation of risk associated with the outcome (or options for alternative outcomes, such as various levels of harvest) of not achieving the objective and advice developed accordingly. This approach has many assumptions, most relevant to this paper is the assumption that the environment which the resource (e.g., a fish stock) interacts with is constant or varies randomly without trend. Climate change, however, is a directional and non-random process that potentially alters both resource state mean and variance, and could render unreliable advice for resource management that does not take climate change into account (referred to in this document as advice that is not conditioned to climate change). Climate change affects the likelihood of achieving most objectives (including making some possibly unachievable) through inter-alia changing how a resource like a fish stock responds to pressures like fishing, and affect its resilience to and recovery from disturbance. During the current period of rapid climate change, management actions and objectives that occur on various temporal scales could be impacted to varying degrees by changing climatic environmental variables that affect biological resource production. Consequently, taking climate change impacts into account could change advice and decisions for resource management. It is therefore prudent to consider approaches to routinely integrate climate considerations in the formulation of science advice in the Department. Climate-informed science advice may or may not differ from conventional advice, but as evidence of climate change impacts on marine ecosystems continues to accumulate, it is becoming increasingly necessary that the “best available science advice” takes environmental variation and climate change into account in the advice provision process.

A changing climate introduces both trend and autocorrelation in the mean and changes in the variance (usually increasing variance) of environmental ecosystem conditions affecting biological resource state and dynamics, and therefore the resource itself. These potential changes include both short-term departures from the observed range of natural variability (i.e., increases in the magnitude and/or frequency of extreme events) and mid- to long-term departures characterised by spatial and temporal autocorrelation and when persistent over several years, directional trends. Accounting for climate change in advice will involve a process defined in this paper as climate change conditioning of science advice (CCCA) in which appropriate environmental variables reflecting climate change and affecting resource dynamics are identified and linked to the risk assessment component of the advice through assumed or modelled response dynamics.

CCCA requires knowledge of the productivity and dynamics of a resource and the environmental variables which can influence those dynamics, i.e. there needs to be evidence or knowledge of a causal link between a current resource state, its possible future trajectory, and one or more variables that are impacted by climate change. One approach is to incorporate this process knowledge directly into the models used for resource evaluation. However, the dangers of model misspecification of such an approach is large owing to the inability to distinguish cause from correlation (Sugihara et al. 2012), and the lack of knowledge of the shape of the functional relationship, even when evidence of causality is adequate. Therefore, it is useful to consider climate conditioning not as a way to provide a more complete mechanistic explanation of biological processes that can decrease variance due to environmental changes, but as conditioning of the advice to account for incremental risk due to potential effects of environmental changes.

The difference between the two is subtle but important. The former is a process-based scientific exercise focused on median predictions about future resource state. The empirical data and process-based knowledge are afforded high credibility, and statements about future resource state are probabilistic but considered reliable. The latter is a risk-based approach that focuses on how uncertainty in the probabilities of achieving objectives with certain assumed risk levels is estimated and communicated in the advice without necessarily assuming the causal mechanisms contributing to the risks are known well enough to represent them mathematically. The former approach is concerned with ***how*** climate change affects the biological processes while the latter approach draws attention to management actions, couched in risk language, that might be implemented to mitigate the climate change impacts on the resource.

Climate change conditioning augments uncertainty statements with the additional uncertainty arising from the inclusion of climate variables in those processes relevant to the formulation of the advice. The advantage of the risk-based approach is that risk assessment, which deals with uncertainty in the evaluation of resource state and dynamics, readily translates to risk management, which deals with choices among management options within acceptable levels of risk. A manager can make clearer decisions based on the level of risk associated with their decisions, and evaluate performance of management options more reliably with climate change conditioning, even if the uncertainty of individual outcomes is greater. Advice options can then reflect the change in risk owing to hypothesized or demonstrated impacts of climate change on resource state and dynamics, without having to specify all relevant processes analytically.

Climate conditioning may have little impact on some advice and more on others. It may be that resource sensitivity to environmental conditions is sufficiently low or uncertainties about other processes is so high that adding the complexity of environmental variability and climate change to the basis for advice does not change the uncertainty profiles markedly (i.e., no improvement in risk management of human impacts can be achieved with climate conditioning). However, there is substantial evidence that advice on the impacts of human activities on biological resources is often improved when it is conditioned on environmental conditions and climate change (Busch et al. 2016; Fulton et al. 2016; Tomassi et al. 2017), meaning that the investigation of possible effects should be the default. Advice conditioned in this way should lead to climate resilient strategies for management of biological resources.

1.2 ADVICE PROVISION IN THE DEPARTMENT IS RISK-BASED

There are multiple kinds of science based advisory products produced in the Department each year. The common characteristic of the advice is that it is essentially risk-based advice. That is, the advice includes estimating i) the state of a resource, ii) the probability (or risk) that this state metric is already at or below[1] the relevant biological reference condition and iii) the probability (or risk) that the state of the resource would be at or below biological reference conditions under one or more alternative management scenarios (or actions by resource users). When a management action is taken, none, some or all of the three steps may not be explicit but something is assumed about each one. Advice is intended to inform choices about future actions and therefore, implicitly or explicitly, the probability of status in the future relative to a

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[1] This approach applies equally when the management concern is for the state variable exceeding a biological reference point; a concern more likely to be encountered in advice on habitat and environmental quality than population status. The rest of this document will be framed around the population context, but this is done to make the line of reasoning more readily followed, not to be the restrictive in allocation of the framework.

reference condition. It may not always be apparent that this is a form of risk analysis because thresholds or resource evaluations may not be named as such. In some cases the formulation of risk may be explicit, such as a continuous probability density function of being above or below a reference level as the pressure on the resource (e.g., harvest of the stock) increases, or a decision table associated with the risk of alternative actions maintaining status quo or else of being at or above the reference level.

These common methods of presenting risk may be established in fisheries advice but risk-based advice is also present in other areas of DFO jurisdiction. For example the Fisheries Protection Program (FPP) may follow a protocol which requires that a permanent fish habitat alteration must be offset by a habitat restoration or enhancement elsewhere that is of equal value. Analysts providing such advice or a directive will have estimated or assumed the productivity of the habitat in its current state, and how productive the habitat would be after alteration by the undertaking of a particular project. A difference between the FPP and the fisheries examples is that FPP decisions require the planned or anticipated alteration to be treated as a deterministic estimate of “loss”, used as the target for habitat enhancement at an alternate site. The analyst then must estimate or infer the pre-enhancement productivity of the alternate site, and estimate how that productivity is expected to increase as the habitat is “enhanced”. The amount of offsetting required implicitly assumes that the *enhanced* productivity is sufficient that the risk of not achieving that target with proposed offset is less than 50%. (If it were >50% a long term decline in habitat productivity would correspond to an acceptable outcome). The estimates of current and future productivities of both the habitat to be altered by the work, undertaking or activity (WUA has a specific definition in the Fisheries Act (R.S.C., 1985, c. F-14, Updated April 2016), to which we add fisheries - WUAF, Annex D) and the habitat to be improved by the offsetting are typically treated as if they were made deterministically, with only the amount of enhancement as the variance giving a continuous risk function (more habitat enhanced, lower risk of not fully offsetting loss). In particularly data-rich settings the estimates of both present and future productivities of the impacted and the enhanced habitats can also be made probabilistic and a risk profile more fully reflecting uncertainties can be estimated. However, the uncertainties in productivities are based on patterns of historical variation in fish populations (or other variables reflecting habitat “quality” according to the FPP) in the type of habitat where the WUA is to occur, and consequently assumes that the factors causing that variation have not changed.

Risk-based advice in the Department is provided for at least two different purposes:

Tactical advice: science-based advice developed to inform managers of the relatively short term impacts of a WUAF. Tactical advice is the dominant advice in recurrent advisory processes, where advice of the same nature is updated with new values at least once every few years, for example in advice for setting fishery quotas. Tactical advice is intended to inform on the risk of passing a pre-specified harmful threshold for resource depletion that could result from a change in WUAF. In fisheries, this could be the risk that, as catches increase, a specified acceptable exploitation rate would be exceeded, or the spawning biomass would fall below an accepted lower reference point.

Strategic advice: advises managers of impacts of a WUAF over longer terms than tactical advice. Strategic advice might inform managers of the probability of keeping a resource at or above a target (“healthy”) level over a period of time in the future, or the possibility of reaching or getting above that level in a fixed period of time, if specified management actions were taken or activities allowed. In fisheries, this could be the probability of getting a fish stock above a target (like biomass giving maximum sustainable yield - Bmsy) in two generation times as a function of the exploitation rate allowed each year. In cases where advice is rarely updated or the impact of the WUAF is permanent or long lasting (e.g., a permanent habitat alteration or destruction) then the distinction between tactical and strategic advice becomes less meaningful, although often at the cost of making evaluation of cumulative effects of multiple WUAF more important.

Strategic advice over long time scales and advice which is infrequently updated is the kind of advice that is more likely to have a risk profile made conditional by an altered climate (A'mar et al. 2009, Brunel et al. 2010, Freon et al. 2005, Punt et al. 2013). Although this is true as a broad generalization it is not a rule since some biological resources may be sufficiently vulnerable to short term environmental pressures from a changing climate that tactical advice risk profiles would be affected. In such cases, both a deep understanding of the processes linking productivity and/or spatial dynamics to environmental variables and accuracy and precision in the correct environmental measures and their relationships to resource dynamics are needed for reliable advice (De Oliviera and Butterworth 2005, Deyle et al. 2013, Gjoestaeder et al. 2014.). Less quantitative understanding of the effects of a changing climate on a resource can be incorporated via alternative means of capturing uncertainty around the status estimate. We introduce options for cases where impacts are likely but process-based understanding is lacking.

In the fisheries sector, the Precautionary Approach (PA) framework (FAO 1996, DFO, 2006, Fig. 1) combines tactical and strategic objectives in the formulation of science advice for management. Advice on short-term fishing mortality (F) resulting from increasing levels of harvest (i.e tactical) is formulated in relation to longer-term benchmarks for exploitation rate, and, when necessary, rebuilding goals (i.e. strategic). Three features of the PA framework are relevant to CCCA considerations; i) Advice is typically expressed as the probability (or risk) of a stock being in any of three stock status zones (healthy, cautious or critical) as a function of possible removals, both at present (tactical), and in the coming year (or few years) (also tactical); ii) there is an upper limit on F, regardless of how large the spawning stock biomass (SSB) may be in a given year, to maintain the stock within the healthy zone into the future (both tactical and strategic); and iii) the values of the boundary limits on B and F (which determine the three zones) are assumed to reflect stable stock productivity parameters (strategic).

Such a risk-based decision making framework is highly relevant to develop climate-informed science advice, and is applicable to all DFO science sectors, as long as some form of specified targets (goals for management to try to achieve or maintain) and/or limits (conditions of resource status or pressure to be avoided with high likelihood) can be informed by evidence-based science and defined explicitly by management or implicitly by legislation or policy. All science-based advice in the Department is essentially risk-based advice with implicit time scales that suggests an operational definition on the relevance of climate conditioning advice for biological resource management:

Climate-change-conditioned advice (CCCA) explicitly takes climate change into account when estimating the probability that an objective is being met (e.g., a population is above its target), given a specified pattern of actions regarding a work, undertaking, activity or fishery (WUAF).

Updating risk-based advice occurs at different frequencies: annually, recurrent, periodic (multi-annual) updating, or one-off and permanent (Table 1). Including climate change in risk-based advice adds the consideration of the magnitude and recurrence of departures from reference environmental conditions. This requires specifying reference environmental conditions that serve as norms or benchmarks for the state of the environment, just as targets for properties like biomass (B) and fishing mortality (F) for a stock and fishery serve as norms for stock status and exploitation level. However, there is an important difference in that the source of the norms used to set the reference conditions (targets and limits) of B and F are rooted in policy, legislation and binding agreements (such as Maximum sustainable yield (MSY) in The United Nations Convention on the Law of the Sea (UNCLOS) and the Fish Stocks Agreement). They are interpreted consistently for individual stocks, whereas the norms for the environment are intended to bound the range of conditions over which our knowledge of the system and its dynamics has been developed. This means that the risk associated with various management options is conditional on the state of the “current environment” relative to the “reference environment” just as the risk of different management options is conditional on the state of the resource and human pressure relative to their respective reference conditions. When the state of the environment is not explicitly acknowledged in the advice, the advice is *de facto* assuming that the environmental conditions relevant to the resource assessment are within their respective norms. Consequently as long as there is a chance that the background environment is changing, there is also an implicit expiry date associated with the advice. Therefore, the classification of advice as tactical and strategic requires a more explicit statement of expiration. Table 1 attempts to provide guidance as to time frame of validity of advice and thus expiry dates relative to the date of provision.

Table 1: Characteristics of some broad areas of science advice activities in the Department of Fisheries and Oceans, and likelihood that climate change conditioning will affect the risk-based component of the advice. [1] Conditions considered information moderate or better; [2] the upper bounds depend on the generation time of the stock; [3] maintain ecosystem structure to support function [4] a temporary measure that will affect habitat but will be removed.

	Advice type	Main WUAF type	Objectives & thresholds [1]	Objective category	Validity & expiry	Advice update frequency	Possibility that climate change conditioning will change risk profile
Aquaculture	Tactical and strategic	Nutrient loading, carrying capacity	Prevent ecosystem damage, maximise culture production	Sometimes explicit, often implied quantitative	1-20 years	Once	Possible
Aquatic invasive species	Strategic	Multiple	Prevention	Explicit quantitative	As necessary	Once, sometimes repeated	Very possible
Ecosystem approaches (including multispecies)	Strategic	Fishing	Relative abundance [3]	Explicit or implicit quantitative	~5 years	>5 years	Possible
Fish habitat destruction with recovery [4]	Tactical into strategic	Habitat disturbance	Status quo production	Explicit quantitative	1-10 years	1-10 years	Possible
Marine protected areas and spatial planning	Strategic	Multiple	Protection of status quo	Implicit quantitative by species	10 years or more	Once	Very possible
Permanent fish habitat destruction	Strategic	Habitat destruction	Status quo production	Explicit quantitative	permanent	Once	Very possible
Salmon enhancement	Tactical and strategic	Production schedule & release dates	Escapement targets	Explicit quantitative	1-5 years	Once	Possible
Single species recovery planning	Strategic	Fishing	PA reference points and recovery target	Explicit quantitative	5-15 years	3-8 years	More possible
Single species stock assessment	Tactical	Fishing	PA reference points	Explicit quantitative	1-5 years [2]	1-5 years	Less possible
Species at Risk	Tactical and strategic	Fishing, cumulative forces	Recovery targets	Explicit quantitative	1 year to 3 generations	Once, sometimes repeated	More possible

This document is developed to show the risk-based nature of DFO science advice and how this can naturally be extended to incorporate climate change effects in a manner comparable to how any other factor affecting the management risk profile would be considered.

A consistent risk framework will enhance scientific and management foresight and provide a set of rules for developing CCCA to inform decision-making. Ideally advice on decision making should be derived from process-based assessments of the state of the resource and response dynamics to WUAF pressures – which would necessarily also provide mechanistic forecasting ability of the responses of the resource to climate change impacts. Both are typically difficult and often lengthy to achieve, if at all possible. However, there is increasing evidence that the possible impacts of climate change on the risk profiles may be large (Hollowed et al. 2013), as departures from reference environmental conditions violate random environmental state assumptions and contribute additional uncertainty in the assessment and management process. If this additional uncertainty is not captured in the advice, decision-makers are not reliably informed about the risks associated with the available management options. Consequently, strategies for developing CCCA need to be robust, as they will typically be applied in knowledge-poor situations. CCCA is likely to be more cautious compared to standard advice and with some yield (or other opportunity) foregone under “typical” conditions. CCCA will, however, better manage the risk of substantial losses due to weakly quantified but potentially large climate-driven changes in resource productivity and climate driven constraints on resource dynamics (Brunel et al. 2010, Hilborn 2012).

2. A RISK-BASED STRATEGY TO DEVELOP CLIMATE-CONDITIONED SCIENCE ADVICE

Our objective is to account for the potential effects of environmental variation and climate change in biological resource management, in the form of quantifying and representing the uncertainty contributed by environmental deviations from reference conditions in the evaluation of the risk of a human pressure on that resource.

Risk equivalency in resource management advice is a means of ensuring that management decisions can been seen as risk equivalent, notwithstanding differences between the advisory contexts, the level of data, resource dynamics, models or process knowledge about the resource dynamics, and assessment of its current state. Risk equivalency leads to a consistent application of risk for decision making. It has been applied in science advice for management of Australian fisheries to cope with differences in uncertainty across different tiers of data and process knowledge richness and ensure the consistent advice between data rich and data poor assessments (Fulton et al. 2016). Risk equivalency is achieved through the inclusion of “buffers” which are factored directly into formulation of advice on managing fishing activity (or other pressure on a resource). The buffers are intended to systematically reduce the level of activity recommended, as uncertainty in assessing the relevant risks increases. Thus the risk equivalency strategy is consistent with the precautionary approach (FAO 1996). Risk equivalent strategies have also been applied in the USA in keeping with their sustainable fisheries policy (Punt et al. 2012).

The Canadian sustainable fishing policy is consistent with the standard precautionary approach (PA) framework (DFO 2006). Just as the fisheries PA policy was developed as a sectoral implementation of the much broader concept of application of precaution in decision-making about pressures from diverse human activities (FAO 1996), the specific DFO PA framework for fisheries is easily generalised to most human activities managed by the Department (Fig 1). The assessment of a resource’s state relative to established reference points and the level of human activity relative to sustainable levels are captured by Kobe plots (FAO 1996) in fisheries, which can also easily be generalised to different activities because it defines the safe operating space for management (Fig 1). These diagrams inform how a human activity should change given the evaluation of the resource state. This is illustrated in the case of the DFO PA broken stick plot while the Kobe plot shows zones of acceptability for resource state and human activity causing harm to the resource given established reference levels.

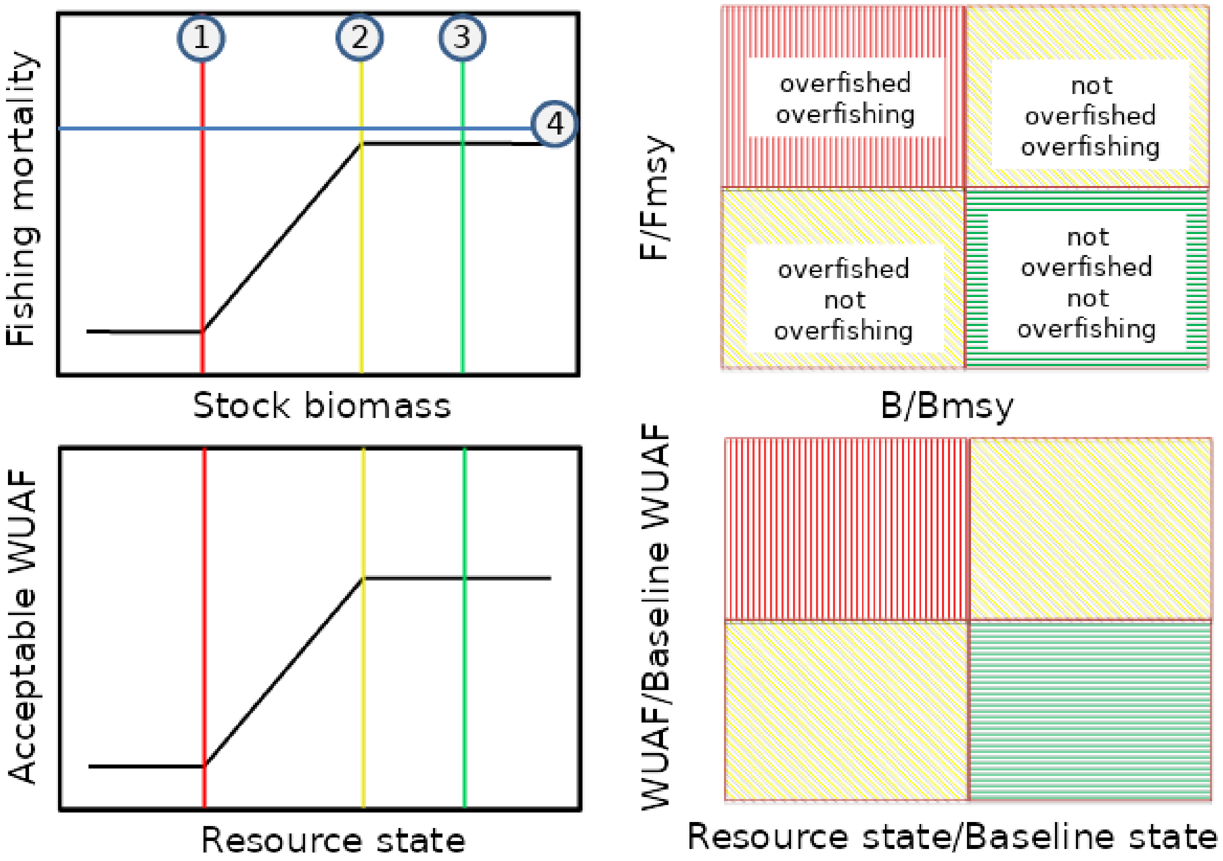

Figure 1: The Department of Fisheries and Oceans precautionary approach for sustainable fisheries (top left) generalised to any kind of human activity affecting a biological resource (bottom left). Red (1), yellow (2) and green (3) blue (4) lines represent the limit reference point, upper stock reference point, target reference point, and limit reference point for fishing mortality respectively, for resource status. The broken stick represents the rule for managing the human activity given the evaluation of resource state. The right panels are Kobe plots which reflect the outcome of past decisions, providing an overall picture of zones of acceptability given the resource state evaluation and the level of activity relative to acceptable reference values. Projected values can also be shown on Kobe plots. The upper left is then "excessive pressure and resource depleted relative to target", the upper right "excessive pressure, resource not presently depleted"; lower left is "pressure sustainable, resource depleted, and "lower right is "pressure sustainable and resource not depleted".

In the broken-stick model, uncertainty can be captured by the distance on the x-axis between the upper stock reference point (USR) and the lower stock reference point (LSR). The LSR represents the value below which the likelihood of serious or irreversible harm is unacceptable (for a stock assessment, the SSB below which "productivity is impaired"[2]). The USR can represent error estimation about the LSR or in practice it may simply be an intermediate point between the LSR and target. At any one time, stock size can be evaluated relative to the reference points and the fishing mortality rate can be determined by applying the broken stock harvest control rule to the median stock size estimate. Given the uncertainties in the estimate

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[2] Phrase from the Marine Stewardship Council" assessment criteria. Various jurisdictions use various phrases for this point on an SSB axis, but the concept is the same. "impairment of productivity" is a useful concept, because it is easily generalizes to any specific ecosystem function (including but not exclusively "productivity") provided by any ecosystem structural property (including, but not exclusively "biomass" or amount).

and productivity parameters, the probability of achieving the objective (e.g., target reference point) in a certain time period with a certain risk level can be assessed.

Little systematic guidance has been developed about how the PA framework can be adapted when a population parameter is different from the past states that conditioned the assessment[3] - a phenomenon known as non-stationarity in production (although, see DFO 2012). Although risk equivalency has been considered primarily as a means of conditioning risk to uncertainty for stocks with different levels of data, it could also be used to condition advice for non-stationarity in production. There is substantial evidence (summarized in section 1.1) that climate change could affect various stock production parameters. Consequently, risk equivalency concepts could be similarly used in Canada when considering the impacts of climate change on advice for management of human impacts on biological resources. Specifically for single species fish stock assessment, climate change conditioning factors (CCF) could be applied to fish catch levels to ensure that advice is climate conditioned going forward.

Examples of how climate conditioned single species stock assessment advice could be developed is outlined in Annexes A-C.

Developing CCF over a range of environmental and stock conditions is the key challenge in developing a general CCCA for fish. Developing and applying CCF becomes increasingly important as environmental variables display two features: i) a high likelihood of responding to climate forcing and ii) a demonstrated or inferred likelihood of impacting the resource dynamics going forward. Their impact on a resource’s vulnerability to climate will be a function of the specificity, susceptibility and adaptive capacity (or generally, the sensitivity) of a resource; the magnitude, frequency and recurrence of change in the environmental variables over the time scale of the advice; and the level of confidence in the data available to assess both the resource and environmental state (ICES 2017).

3. DEFINING AND TRACKING ENVIRONMENTAL STATE

3.1 DEFINING OF THE USE OF “E” IN THIS DOCUMENT

Throughout this document the symbol E will be used to represent environment, sometimes appearing in slightly different ways. [E] written with square brackets represents the concept of stock external variables that affects a stock’s production. An E variable (written just as capital E without brackets) is the time series of quantitative measures of an environmental forcer like temperature or even an ecosystem variable like predator abundance which affects a stock’s productivity. An E variable could also be some kind of combined vector of individual E variables or a composite time series variable for example a principal component. Once an appropriate E variable(s) is chosen, it will remain for the researcher to define baseline conditions for that variable, we refer to those conditions as E_{base}. E_{base} therefore represents conditions to which past and future states can be compared and often, but not always, E_{base} will represent a set of stock external conditions that may be considered a reference or ‘normal’ state. E_{base} is therefore often the mean of a particular period of time in the E variable time series and it is a scalar. In some cases, E_{base} may be a vector representing moments of the E variable time series, e.g., a baseline mean and a baseline variance (Landres et al. 1999), therefore $[E]_{base}$ represents the baseline ensemble of environmental conditions which could be multivariate and involve different moments of the same variable in a baseline period.

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[3] The difference may be in the mean of the population parameter change, but could also be changes in higher moments – variance or skewness of the parameter.

3.2 CHOICE OF E VARIABLES

We collectively refer to environmental variables that are potentially affected by climate change and known or likely to affect resource state and dynamics, as environmental state variables E. Together, E variables and reference environmental conditions (E_{base}) provide a resource-specific measure of environmental state (ratio of E/E_{base}) used to track environmental deviations and environmentally-condition the risk of resource utilisation and related science advice. Choosing one or more E variables will be resource and/or ecosystem specific and a function of i) the available data and data quality (including spatial and temporal resolution); ii) the likelihood and relative rate of change of candidate environmental variables to climate forcing; and iii) potential relationships and interactions between variables. Based on these factors and depending on the resource under assessment, it might be useful to consider a single E variable or an ensemble of several E variables and their relevant statistical moments. In most cases, E variables will need to be spatially reduced to the resource management area (for inclusion in risk analysis).

In terms of relevance for tracking and detecting climate change, the World Meteorological Organization recommends a set of variables that are relevant, feasible and cost effective to collect (Bojinksi et al. 2014, WMO 2018), while literature sources generally define four principal environmental variables for aquatic resources and ecosystems: water temperature, pH, oxygen concentration and nutrient availability/primary production (Pörtner et al. 2014; Henson et al. 2017). Consensus has formed over which environmental parameters in Canadian marine and freshwaters are changing or are most likely to change (DFO 2013a,b,c,d). Ocean parameters with the highest likelihood of change across three oceans included temperature, salinity, oxygen concentration, sea ice parameters, stratification, pH, circulation and sea level.

Fully defining one or more resource-specific E variable(s) is a major task, but when developing approaches, the underlying concepts can be represented by a single E variable such as temperature, quantified as a central tendency parameter (e.g., mean annual temperature) (see Annexes A and B). While the use of a single environmental variable that is well-measured and well-correlated with other variables can serve as a reliable starting point, ultimately the aim should be for the E variable to explicitly account for the multidimensional character of both climate and the environment (with the inclusion of multiple environmental variables), and to account for changes in both the mean and variation (and correlations between) variables over annual and intra-annual (i.e., seasonal) time scales. Note that the framework being discussed here does not promote reducing the problem of addressing risk equivalency and climate change, rather it is a pragmatic simplification to allow progress in the face of typical limitations on available data, system understanding and analytical tools.

Higher order statistical moments of a variable’s distribution, such as variance, skewness, and kurtosis, may be as important as central moment parameters (mean or median) in defining E and E_{base}. A single variable such as temperature may represent the net influence of multiple environmental drivers for a resource, and/or be the only variable that is consistently available over historical time series for a given region. In any case when attempting to assess deviations from a reference environmental space for a resource, annual means or absolute values of the variable(s) alone may not be as important the resource as variations during critical periods (or seasons). This is because biological resource dynamics (e.g., processes linked to resource productivity and/or availability, including recruitment success and changes in movements/distribution), can be a function of either or both the magnitude of, for example, temperature deviations during a specific period or the timing of a particular range of temperatures during the annual cycle. Knowledge of life-stage specific optimal ranges (or seasonal optima) and tolerance thresholds is likely to increase the meaningful use of E variables, depending on the property of interest, and should always be taken into account in choosing E variables. For example, if resource state is evaluated as annual recruits at age three, the choice of E variables will need to reflect environmental conditions affecting recruitment success over the three year pre-recruitment period.

If a vector of individual environmental variables is preferable or considered more appropriate, the vector may be developed assuming independent (additive or multiplicative) effects for the suite of environmental variables or their joint probability distribution (Nadeau and Fuller 2015). In both cases weighting of the different variables may be justified, if information is available, to account for differences in resource exposure and sensitivity to different drivers. Joint probability distributions serve to capture potential changes in the relationships between variables over time and to relax the independence assumption. They do however rely on distributional assumptions for the different variables considered. Dimensional reduction using appropriate ordination methods or climate overlap statistics will be useful to ensure parsimony when defining environmental variables and tracking environmental state (ratio of E/E_{base}) for a resource. Overlap statistics may also serve to avoid averaging or reducing independent variables with different trends (e.g., small change in one vs large change in the other; Nadeau and Fuller 2015).

Regardless of the approach and method adopted, researchers will have to invest time and effort to identify and build empirical and process understanding of the specific environmental drivers that are most relevant to defining and monitoring the state of the environment for their system(s) and resources of interest. Our goal here is to stress that E variables can be single- or multidimensional and consist of both different moments and different aspects of the same environmental variable(s).

3.3 REFERENCE ENVIRONMENTAL CONDITIONS (E_{BASE})

It is a *de facto* assumption that organisms are adapted to the historical climate variation where they occur (Scholander et al. 1950). If they are not adapted (for instance with post-glacial relict populations), conditions are at least within the habitable range. Consequently historical variance in E variables should be considered as a baseline in any decision making related to climate change. Reference conditions of E variables (E_{base}) are defined by the frequency, magnitude, and time history of variation in E variables, and the certainty we have in measuring or modeling each E variable. Local interactions of the long-term means, variation and correlation of multiple variables overlaid on seasonal cycles determine E_{base}, which then shape and possibly regulate biological and ecological patterns of the resources. These conditions thus constitute ‘the environmental and biological norm’ for evaluating resource status and variation. The introduction of climate change considerations serves to capture environmental conditions that deviate from the patterns in E_{base}, including new extremes and reduced or amplified variance in time and space.

E_{base} is not a new concept (Landres et al. 1999), but one that becomes explicit and necessary if a changing climate [E] is to be considered in resource evaluation and management process. E_{base} is always integral to conventional stock assessments, but is rarely treated explicitly. Rather, it is assumed that environmental variation is random, of stable variance, and computations and advice are unlikely to be improved by including an explicit manifestation of [E] in the assessment of resource status. Even when this assumption is rejected, and some environmental variable(s) are included analytically in the assessment (Pepin et al. 2018), reference environmental conditions are rarely specified. Instead, the environment is treated as a covariate or dynamic variance in stock dynamics, with advice either chasing environmental variation or trying to anticipate it by a year or two. The population dynamics parameters in the assessment usually are kept constant, and the environmental influence is added in the assessment computations as one or more independent driver(s) of the population dynamics, whose effects on the dynamics are bounded by the model structure. With the definition of E_{base}, the CCCA approach takes the step of considering the influence of environmental variables relative to the environmental conditions that occurred during the period (or a subset of the overall period) during which data were collected and resource dynamics parameters were estimated. If the environmental conditions remain within the E_{base} conditions, little gain may be expected from adding environmental complexity to the advice. As current or projected [E] becomes increasingly different from $[E]_{base}$, their potential impact might not be well-captured if they are merely used as an E covariate in the tactical analyses when in reality several factors of a resource's dynamics might be affected. Hence the more strategic approach of making resource advice conditional on climate conditions.

We identify two ways to determine E_{base} as it relates to resource status datasets directly:

1. If the biological norm (reference state level for B and F) is selected by choosing a set of years when the resource was considered "healthy" and the imposed pressure (such as fishing) was "acceptable", then all environmental conditions during those years necessarily define the "standard" environmental conditions for the resource (E_{base}). If this constraint for environmental conditions is considered undesirable operationally, then the entire basis for choosing reference values for resource state (B) and pressures (F) based on years when conditions were considered "normal" or "acceptable" also requires careful re-examination.
2. If the biological norms (biological reference points - DFO 2006) is determined analytically by methods such as fitting a stock-recruit (S-R) relationship, years with S-R points that are exceptional deviations from the fitted relationship can be used to identify years when the stock dynamics are unexpectedly high or low (depending on the sign of the deviation). An outlier check to assess whether environmental conditions in those years were outside the norm for the resource (using any acceptable method for statistical detection of outliers) should be performed. If outliers are detected, E_{base} would correspond to the environmental conditions bounded by the outliers, but exclude them. If no outliers are detected, it is the work of the investigator to assess patterns and relationships in environmental data to determine reference conditions for parameters and locations of interest. However, if no outliers are found in the relationship between the resource state and the variable(s) affected by the environment (e.g., outliers in R given the SSB) then the range in environmental conditions during the full period from which the S-R data were taken becomes the E_{base}.

In data-limited cases where only a short and recent time series of environmental data are available (e.g., last 5 years), empirical knowledge derived from experimental or other independent studies may inform the determination of E_{base}. For example, a temperature range (mode, median and minimum/maximum values) identified in a laboratory as optimal for growth, may be used to delineate E_{base} for the resource until further environmental observations become available. The same information may be inferred based on empirical or mechanistic understanding established for a parent or similar resource in another (parent or similar) system.

3.4 ENVIRONMENTAL STATE

The environmental state for a resource can be standardised as a ratio deviation from reference conditions (E/E_{base}) just as in many advisory contexts the ratio of B to Blim or Bmsy (or the same for F) is featured in the advice. For this reason, it is important to consider variation in E_{base}. As a general rule, a point estimate for a mean state reference (e.g., Bref) is used for expressing relative (or more rarely absolute) deviations of annual state values from the reference, even though it is expected that a "healthy" (or cautious or critical) state will naturally show some (often substantial) variation around the mean (which is treated as the management goal). The same goes for the reference level for a human activity (e.g., Fref). Substantial debate can occur about the acceptable bounds for the ratios of resource status and human activity (e.g., B and F) around their targets, but that issue would have to be confronted with *any* approach to bringing climate change considerations into assessments and advice (FAO 2016, Garcia and Rice 2018).

In the case of E_{base}, both the form and the extent of variation around the mean must be considered. This is because the range of environmental variation is not always either uniform or normal. Environmental variables can be highly skewed due to natural asymmetry in physical or biological properties – for example in parts of the NW Atlantic, waters cannot get colder by more than a couple degrees below the mean before it freezes; whereas lakes, embayments or surface waters may get several degrees warmer than "average" under hot summer conditions. Thus, more complex statistical approaches for expressing deviations from skewed or bounded E_{base} distributions should be explored. Ideally, uncertainty in all reference states (reference resource state, reference level of human activity, and reference environmental state) should be assessed and propagated throughout the risk assessment.

4. ENVIRONMENTAL CONDITIONING OF RISK AND ADVICE

The risk assessment approach on which the proposed CCCA is built quantifies the probability *P* of a resource being in a given state relative to established reference points (e.g., B/B_{msy}) and the level of a human activity relative to acceptable levels (e.g., F/F_{msy}). This approach implies that the true state of the resource is unknown, but that there is sufficient information to approximate resource status within some confidence bounds or express its status relative to some benchmarks. Thus for a given pressure level and objective to maintain resource state B above some reference threshold (e.g., a biomass reference point, B_{ref}):

$$Risk = P(B > B_{ref})$$

This evaluation of risk corresponds to the y-axis in Fig A1.1 (Annex A) and ties into risk management, which deals with the level of acceptable risk associated with the different management objectives (e.g., each of the three panels in Fig A1.1 (Annex A)). The relationship between the probability of a resource being in a given state and the level of a human activity that is being managed (e.g., x-axis on Fig. A1.1 (Annex A)) is what we call the risk profile. This profile quantifies the response of the resource to human pressure and describes a suite of management options in terms of fishing mortality adjustments required to meet an objective, considering uncertainty in resource state evaluation. Environmental conditioning of the risk first consists of adjusting the risk profile considering uncertainty in resource dynamics contributed by environmental deviation from reference conditions (i.e., E/E_{base}). Secondly, it considers the effects (potential or realised) on the resource state and dynamics in both tactical and strategic space.

Environmental departures from reference conditions will act as an additional direct or indirect pressure on the resource, potentially affecting the risk of achieving management objectives in near-term or projected time scales. Depending on their frequency, magnitude and directionality, environmental fluctuations may contribute bias and uncertainty in resource dynamics (process uncertainty), in the modeled response of the resource to human pressure (model and estimation uncertainty), and in sampling variability and input information (observation uncertainty). Yet while potential sources of uncertainty can be identified and/or anticipated, quantifying the magnitude of their effects is far from straightforward. For this reason, CCCA focuses on the risk profile, i.e., the relationship between the probability of a resource being in a given state and the level of human activity, rather than assuming each aspect of uncertainty that cannot be resolved analytically on time scales necessary for the advisory processes.

In quantitative space, the risk profile results from the modelled response of the resource to the pressures on the resource. Conventional resource assessments typically consider the manageable human activity, such as fishing, as the dominant (and de facto, sole) pressure on the resource, and the responses are mediated by changes in some dynamic properties of the resource (e.g., recruitment, age or size composition, etc). The environmentally-conditioned risk profile(s) (as exemplified in Fig. A1.1 (Annex A)) correspond to the standard risk profile multiplied by CCFs, which are either estimated or approximated (depending on the available data and process knowledge), and become part of the basis of the advice. Should environmental conditioning result in a CCF different from one, maintaining a desired level of risk for the resource management objective, will require adjustment to the level of human activity (e.g., F) relative to reference levels (e.g., Fmsy). Since environmental change can have positive or negative implications for the resource (i.e., correspond to more favorable or unfavorable conditions), CCFs can take on positive or negative values. Consequently, when environmental conditions are in a favourable state for a resource, high levels of the human activity (e.g., harvests or fishing effort) will be associated with low levels of risk of not achieving the management objective(s) in the short term. In such cases, the application of a penalty to rapid changes in human activity can serve to avoid big jumps in pressure intensity and risk when it is uncertain whether favorable environmental conditions will persist over time. However unless such penalties are asymmetrically applied, with much stronger penalties on pressure increases than on decreases, they will also weaken or delay responses to deteriorating environmental conditions. The use of asymmetric penalties can ensure precaution in the formulation of CCCA, while environmental conditioning of the risk will ensure that climate change effects on biological resources are readily detected and incorporated in resource assessment and management process.

Climate change conditioning of risk may require different methods and approaches depending on several factors:

- data availability
- process knowledge
- resource assessment method
- process and observation uncertainty
- magnitude of deviations E from E_{base}
- sensitivity of the resource to [E]

The urgency for developing climate-informed science advice will affected by:

- frequency of recurrence of important deviations of E from E_{base}
- indication of a directional shift in E/E_{base} deviations
- purpose and time frame (expiry) of the advice
- type of management objectives and time allowed to achieve them
- acceptable level of risk of not achieving management objectives
- turnover time of the resource
- current resource status sensitivity and adaptive capacity allowable harm (in the case of negative impacts of climate change)

Future work in developing CCCA could be directed toward developing CCFs to apply over a wide range of the above considerations.

4.1 CLIMATE CONDITIONING FACTORS (CCFS)

Environmentally-conditioned risk profiles can be computed in the assessment model, based on one or more functional relationship(s) between one or more components of the resource dynamics and relevant E variable(s). In such cases, the CCFs are quantitative values estimated by comparing different model scenarios with different assumptions of resource dynamics dependence on E/E_{base} (see data rich and data moderate examples in Annex A and Annex B). Where environmental effects on the resource dynamics are not known and/or there is no accepted assessment method relating resource state and the human activity (i.e., low data or knowledge deficient), but a set of indicators are available to evaluate the risk, CCFs can be approximated using categorical, semi-quantitative scores (categorical or inferential CCFs) based on resource sensitivity information weighted by the magnitude of change relative to reference environmental conditions (E/E_{base}) (i.e., exposure to change) and the level of confidence in the information available to the assessment (Fig. 2) (see example in Annex C). Resource sensitivity to environmental change may be approximated using sensitivity scores derived from climate change vulnerability assessments, considering life history attributes and expert knowledge of resource sensitivity to environmental variation; empirical knowledge on adaptive capacity and tolerance thresholds to specific E variables derived from experimental studies; or inferred data and information available for similar and comparable resources/ecosystems.

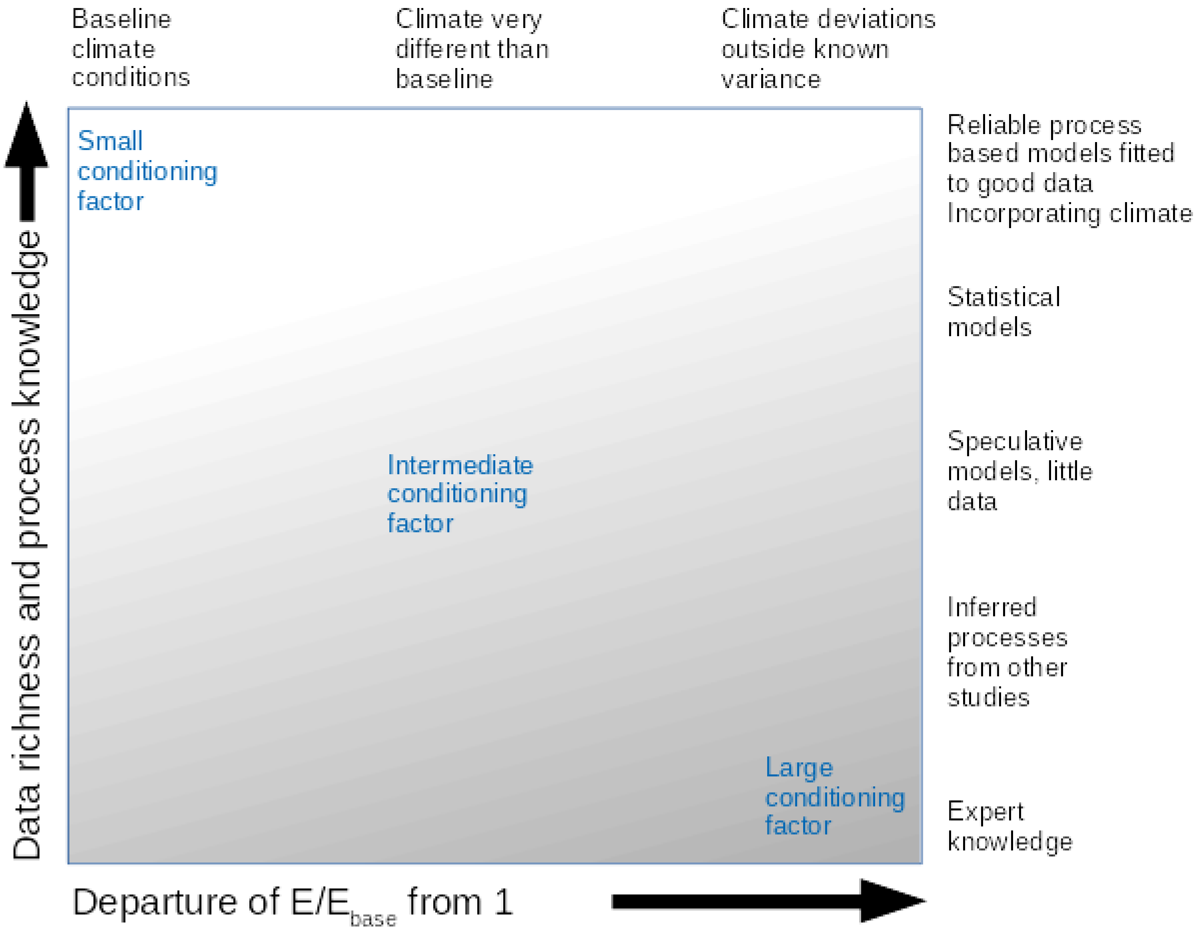

Figure 2: A depiction of how conditioning factors on advice may change as a function of the magnitude of deviations in E/E$_{base}$ from 1 and the amount of data and process knowledge available to discern climate change impacts on the resource. Uncertainty increases with the magnitude of change in E/E$_{base}$ (from left to right on the horizontal plane) and also increases with decreasing data/assessment quality (from top to bottom on the vertical plane). The is a depiction for resources with similar sensitivities to climate change which avoids the depiction of a third axis. Therefore it is important to consider sensitivity of resource dynamics to climate change. Uncertainty scores developed along these axes may be used as a means of determining climate conditioning factors (CCFs) for a variety of data and model situations and climate change scenarios.

Different approaches to specifying or estimating CCF (semi-quantitative and inferential to fully quantitative) can be operationalised as incremental steps to ensure that the uncertainty contributed by a change in the environment is readily incorporated in risk evaluation and related science advice, even though process knowledge of resource dynamics dependence on E may be incomplete. As process-based understanding of the relationship(s) between E variables and resource dynamics and the analytical assessments improve overall, there is increasing ability to estimate the CCF quantitatively in the assessment. The assumption of a linear relationship between the resource state and the environmental state is the very first step under data-limited circumstances, with incremental improvements possible in the CCF approach whenever new knowledge becomes available on the responses of the resource to environmental conditions, human pressure or other relationships.

At present and in most cases, it can be expected that the information required for fully determining robust relationships of environmental state and resource state or dynamic components will be incomplete. Nevertheless, systematically implementing environmental conditioning of the risk will serve to both allow decision-makers to use the limited knowledge available and guide knowledge and data acquisition steps to achieve more reliable CCFs and improve confidence in climate-conditioned science advice.

The two dimensional space considering an axis for data and processes knowledge and an axis for the magnitude of climate departure from baseline (Fig. 2), may represent the first and main step for determining CCFs and developing climate-conditioned science advice. However, CCFs determined in two-dimensional space must also consider, intrinsically or extrinsically, the sensitivity to [E], as this determines the magnitude of the response of resource dynamics to [E] (and thus CCF values). Intrinsic consideration of resource sensitivity occurs where there is a working statistical model and relationships between the resource dynamics, human pressure and E variables. In such cases the magnitude of the response of resource dynamics to E is determined inside the model and is implicitly considered when estimating CCFs. Extrinsic consideration of resource sensitivity occurs where there is no statistical model or statistical relationship. In such cases, two dimensional CCFs are adjusted (for example, using semi-quantitative resource sensitivity scores) in order to account for the magnitude of resource dynamics dependence on E. Thus in contrast to risk equivalency approaches developed and implemented in the USA and Australia, where only the vertical (data and process knowledge richness) axis (Fig. 2) is formally considered, CCF derivation is actually a three dimensional process without the need to explicitly include mechanisms for those temporal changes. For example, allowing natural mortality to vary in time during the estimation process could possibly reflect changes in mortality brought about by increased temperature from climate change. Because most climate-related drivers are expected to be correlated with one another and autocorrelated in time, if there are correlations of environmental variables with population parameters, shorter term tactical projections and advice may well reflect climate change considerations simply by incorporating selected time varying parameters. These kind of models essentially remove the horizontal axis dimension (Fig. 2) if the time varying parameter is thought to represent changes in dynamics owing to climate change. Time varying parameter models, however, usually do not speculate deeply on the cause of the variance (this is seen as their virtue) and the time varying parameters become a sort model of process error. Process error and random effect models are currently in vogue and are elegant in the sense that they need not specify sources of error and they do fit data well, but as such they are a step away from the process model based depictions (Fig. 2) towards statistical models with less process understanding, can be biased (Auger-Méthe et al. 2016) and they may still require conditioning along the data/knowledge axis.

4.2 TIME SCALES OF ADVICE PROVISION IN FISHERIES

DFO Science provides science advice on a wide range of WUAFs, to protect or ensure sustainable use of many aquatic ecosystem components (Table 1). Environmental variation on time scales from interannual to centennial can affect many of those combinations of pressures and state, offering many pathways for climate variation and change to be taken into account in advice. Even considering just the management of capture fisheries there are many needs and opportunities for climate-conditioned fisheries advice. Table 2 illustrates some of the possible interactions of pressure, state and time scale.

Table 2: Components of standard fisheries assessment advice, and a thought experiment to show how they are affected by climate change at different time scales and the possible strategies that science or management might take to deal with it (conditioning).

Component	Variable	Time scale	Possible impact	Possible climate conditioning response
State	Spawning Biomass	Annual	Climate change might cause changes in size-at-age that varies among cohorts,	Making weight at age conditional on E/E_{base} in the year that the cohort was produced, to manage the risk that adequate mature biomass is available for spawning each year.
		Multi-year	Suitable oceanographic conditions for spawning are changing both in extent and position	Making the target SSB to be left at the end of the fishery conditional on E/E_{base}, so adequate spawners are available to saturate suitable spawning volume to manage the risk of impaired recruitment as amount of recruitment needed changes
		Multi-decadal	Species composition and primary productivity change, so food web relationships alter in the ecosystem	Re-evaluating the needs of a new suite of top predators on mid-trophic levels, and bottom of food supply to the system, so new Escapement levels are set for forage species manage the risk of insufficient prey for all predator needs
Pressure	Fishing Mortality	Annual	Overwintering mortality become more variable as winter ice conditions become less predictable	Condition M in annual stock assessments to E/E_{base} with a constant Z goal. Therefore F buffers the climate change impact on Z.
		Multi-annual	Stock becomes increasingly aggregated as suitable habitat space decreases with environmental change	Making the F/effort relationship in the stock assessment conditional on E/E_{base} (suitable habitat space), so changing q is taken into account in the annual quota advice, managing the risk of overharvesting the stock
		Multi-decadal	Recruits per spawner develops a significant long-term trend due to environmental change	Develop a harvest control rule that takes trend in E/E_{base} into account and adjusts the target harvest rate to the trend in the impact of environmental conditions on stock productivity, managing the risk of impaired recruitment
Risk Assessment		Annual	Protected species taken as bycatch enters the fishery area years of favourable environmental conditions	With bycatch rate proportional to effort in target fishery, set a total cap on effort conditional on E/E_{base}, so effort is reduced proactively when conditions favourable for high bycatch occur, managing the risk of exceeding bycatch tolerance for a protected species
		Multi-annual	Mix of species in a multispecies fishery is changing as conditions favoured by different species change at different rates	Make the risk tolerance for exceeding sustainable removal rate of the species least favoured by the environmental trend more stringent than the risk tolerance for other species in the complex, to manage the collective risk of keeping all harvest rates sustainable

Consider a positive deviation in water temperature that affected spatial distribution of a fish stock, and thus possibly change survey catchability, commercial catch per unit effort (CPUE), and the corresponding abundance indices that serve as inputs to the stock assessment. In this case, the change in the environment may affect estimates of stock status by potentially introducing bias and observation error in abundance estimates compared to earlier values in the time series. The same changes may or may not yet affect stock dynamics as implemented computationally in the stock assessment, but using that data point in provision of advice will introduce inaccuracies in advised harvest level. If the value is treated as an absolute estimate of stock size then the advised quota at Fref would be biased in the same direction; whereas if treated as a relative index of stock size but added to a time series of relative estimates it would bias the estimate of trend optimistically for a positive bias and pessimistically for a negative bias.

Tactical advice for this stock will be formulated based on the calculated risk of the stock being in a given state relative to its reference points and current harvest level (safe operational space= P) assuming random environmental variation within the range of natural variability for the stock). The additional environmentally-conditioned risk of stock status would have the risk adjusted for uncertainty in the environmental state (E/E_{base}), with the goal of the adjustment to have the stock be in the same state relative to reference points and current harvest level (safe operational space P^{CC} taking into account environmental effects on stock status proportional to stock sensitivity to temperature variation, the magnitude of temperature change relative to reference level, and confidence in the information available to assess environmental state). Depending on the CCF (factorial difference between P and P^{CC}), tactical advice for the stock may consist of precautionary statements acknowledging uncertainty contributed by a short-term departure from reference environmental conditions and lower confidence in the point estimate for stock status in that year, or may be risk profiles that include a reduced harvest rate or a higher escapement for a given risk tolerance under the environmental conditions expected during the advisory period. There may be a recommendation for enhanced monitoring effort.

Now consider the same positive deviation in water temperature occurring five years in a row, with noticeable changes in stock distribution and survey catchability. The shift in distribution is suspected to have triggered changes in community interactions affecting stock productivity. In this case the change in the environment is expected to affect both recent stock status and dynamics. Tactical advice by year five needs to consider the frequency and recurrence of deviations from reference environmental conditions, as well as knowledge development over the last five years (learning processes initiated in previous years as a result of the explicit consideration of environmental variability in the assessment). In this case, a scenario-based approach could quantify how environmentally-driven changes in stock productivity and survey catchability assumptions in the stock assessment will affect the risk profile (i.e., difference between standard and environmentally conditioned risk). Tactical advice for the stock would acknowledge increasing bias or uncertainty contributed by repeated departures from reference environmental conditions and may have started to explore, test, and even adopt alternative specifications for catchability and stock productivity assumptions in the assessment model. Strategic advice could be developed by projecting scenarios into the future and assessing how the response of the resource to different harvest levels and under different catchability and productivity assumptions may develop under persistent temperature change. How quickly changes are made to the management strategy and objectives for the stock will depend on the strength of evidence as it accumulates (both amount and consistency of evidence, particularly process-based understanding of either or both that the environmental changes will persist, and that the environmental changes really are affecting stock dynamics.

If the same positive deviation in water temperature is consistently detected over the span of perhaps a decade or more, DFO Science should recompute stock reference points under what could now be a new productivity regime for the stock and evidence of climate change impacts, and commence dialogue with other DFO Sectors and external clients of the stock advice on the implications of the results. This dialogue is likely to also include a repeat of a Management Strategy Evaluations (MSE) or other analyses supporting the management strategy in place, and form the basis for appropriate changes to the strategy's reference points, harvest rates, and other management measures that could be affected (e.g., opening and closing times, spatial or fleet-based allocations, etc). By explicitly considering temperature deviations from reference conditions in the risk assessment process at annual, multi-year and decadal scales, the CCCA strategy could allow Science to 1) rapidly detect and monitor potential effects of climate change on the resource; 2) readily account for the uncertainty contributed by environmental change in the formulation of science advice in multiple time scales; 3) initiate research and knowledge development on the effects of environmental change on stock status and dynamics; 4) readily challenge stock assessment assumptions under a potentially new climate reality, and 5) when the evidence warrants, inform revisions to the management strategy to reflect the new environmental conditions.

This risk-based approach to taking environmental change on various time scales into account in science advice should apply widely across many areas of whole or partial departmental jurisdiction in order to account for climate change over this range of advice. A specific example of these considerations in a fisheries assessment advisory context is shown in Table 3. Clearly each case will be context dependent and operationalisation will require specific expertise and take into account the advisory context.

Table 3: Climate related risks across time scales and different kinds of advice in fisheries management. Climate change will alter advice differently depending on which time scale the advice is intended for and possible consequences of including climate considerations or not.

Time	Risks	Analysis (all bullets *possible*, few *certain)*
Short	Erroneous Quotas 1. too high-overharvest 2. too low-lost opportunity	Processes Possibly Involved: a) Growth, Recruitment, Survivorship changed b) Distribution changed Assessment Consequences: a) Averaging out biological variation b) Changes in CPUE and survey indices Improved Assessment Treatment: a) use more accurate annual estimates b) Adjust indices for changes in "occupied space" Requirements to Achieve Improvements: a) Tight relationship between environmental feature and assessment parameter b) Species has defined habitat preferences New Possible Assessment Shortcomings with Weak Treatment: a) Increase variance much more than remove imprecision / bias b) Over-interpret impacts of environment changes in range of envt variable where relationship is weak
Multi-Annual	Same as short; Delay detection of changes in trajectories	Processes Possibly Involved: a) Same as for short term but changes are abrupt and persist Assessment Consequences: a) Most short term consequences plus

Time	Risks	Analysis (all bullets *possible*, few *certain)*
		b) Appropriateness of management benchmarks changes Improved Assessment Treatment: a) Measures in short term plus b) Recalculation of Management Reference Points Requirements to Achieve Improvements: a) Relationship between environmental feature and assessment parameters must have power to detect non-linearities/tipping points b) Estimating multiple sets of reference points more data-demanding c) Persisting changes to species distribution may require adjustments to fishery monitoring and surveys d) Find reliable environmental indicators of step-like productivity changes. New Possible Assessment Shortcomings with Weak Treatment: a) Undermine confidence in management benchmarks if they are changed too soon (false alarms) b) Management risks of delays in changing advice from one regime to alternate are highly asymmetric (high to low vs low to high) c) May be that “regimes” are just multiple but different stable system configurations so each “regime” is unique
Multi-Decadal	Envt driven trends confounded with fishery-induced trends; Relocation of fishery over time (changes in bycatch and habitat impacts)	Processes Possibly Involved: a) At specific places population parameters showing gradient of change b) Community of predators, prey and competitors changes c) stock may change range to stay within suitable environmental window Assessment Consequences: a) Confounding interpretation of assessment results could over- or under- estimate of role of fishery in stock trends b) All density-dependent parameters need careful evaluation c) Assessments will need to have spatial boundaries re-evaluated regularly Improved Assessment Treatment: a) ability to uncouple climate and fishery drivers b) More use of multi-species and size-based models c) Habitat preferences known and limiting Requirements to Achieve Improvements: a) Tight relationship necessary between environmental feature and assessment parameter b) Multispecies / Ecosystem monitoring and rigorous models c) c) Oceanographic models that can predict temporal trends in habitats New Possible Assessment Shortcomings with Weak Treatment: a) Many functional relationships will be predicting outside the range of parameterization data b) Fisheries behaviours likely to change as much as stock, and will affect MANY data streams.

5. DECISION PROCESS FOR DEVELOPING CLIMATE CONDITIONED ADVICE

There are multiple approaches and methods for developing CCCA. Choice of approaches and methods needs to consider the overall knowledge and data availability, resource response to climate change (as determined by the magnitude of environmental deviations from reference conditions and resource sensitivity), and the type of tactical and strategic advice needed (Figs 3, 4). We have provided a general diagram showing the thought process that may be considered when developing CCCA.

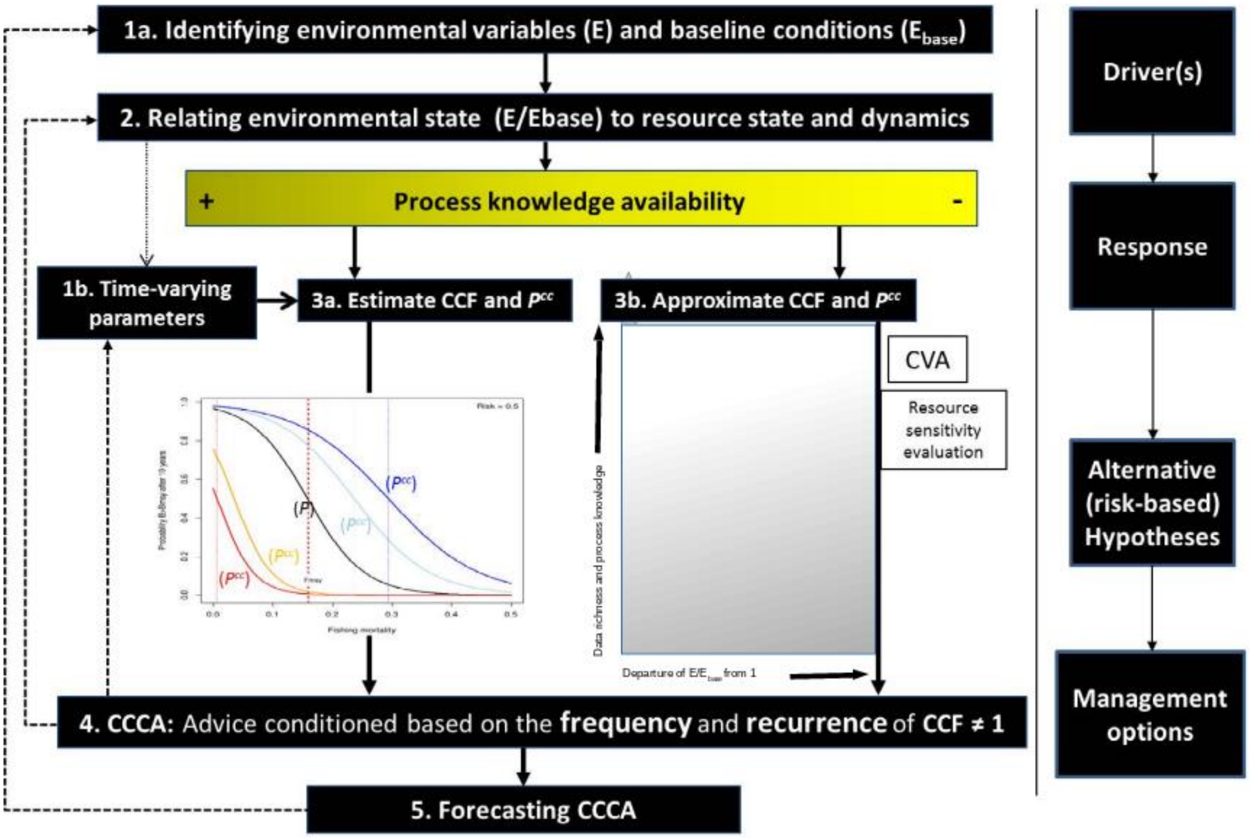

Figure 3: Steps defining the thought process for developing a strategy for providing climate change conditioned advice (left), with key components (right). Solid arrows represent step-by-step process. Dashed arrows represent iterative process. The dotted arrow (time-varying parameters) represents a step based on a priori hypotheses.

Figures 3 and 4 depict a stepwise process for developing climate conditioned advice. Fishery examples of CCCA implementation provided in this document (Annex A and B) are primarily explained for fisheries managed by output controls, e.g., TAC based fisheries. Application of these methods to input control fisheries (e.g., east coast lobster fisheries managed by number of licences, traps, fishing seasons and size restrictions) are possible but there may be added elements. For example, the advice has to consider how the input controls affect the stock (e.g., end-of-year SSB and R) and, depending on the assessment model, the output (e.g., harvest magnitude), as well as how climate change may be altering both the input controls (e.g., effort in time and space) and stock status. These changes may add further complexity to climate change conditioned advice on input control fisheries. This in turn may lead to changes in season length, or change in the number of licences or traps. The interactions amongst input controls may not have a direct path to output so it will be necessary for the assessors most familiar with the particulars of a fishery and biology of a stock to determine what kinds of controls might be the most suitable to effect in order to achieve the risk equivalent management under climate change.

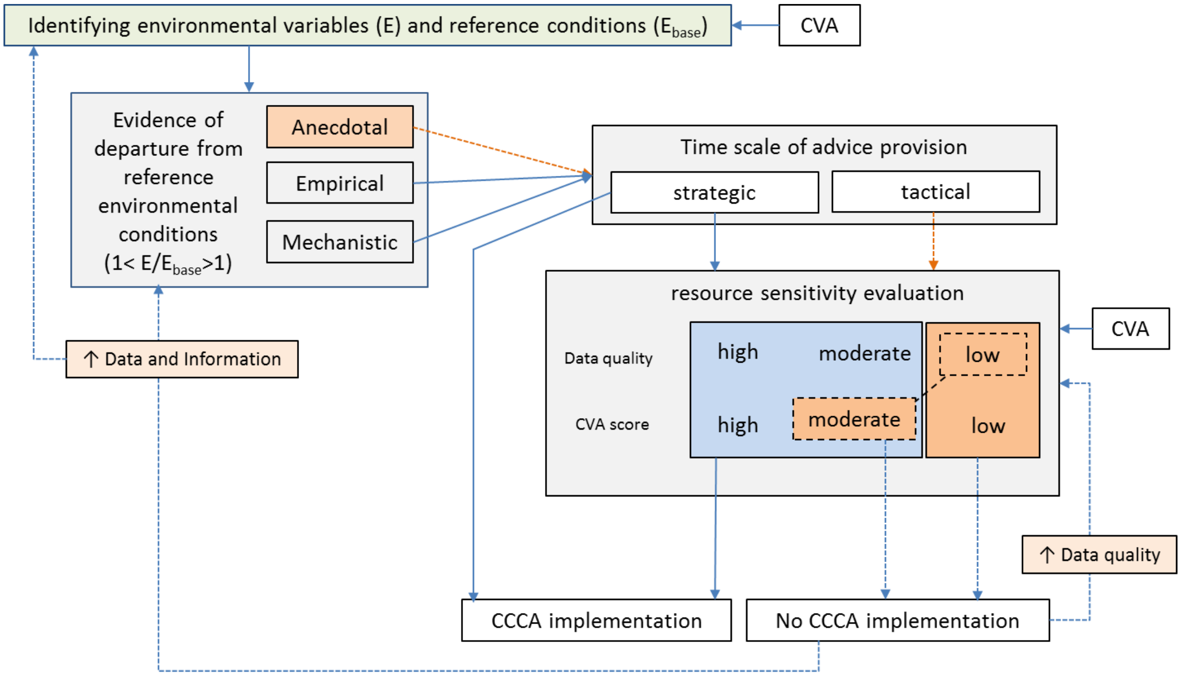

Figure 4: Decision process for determining when and how to develop and implement climate change conditioned advice (CCCA) for a resource, given the knowledge basis for environmental state evaluation, the nature of the advice sought, data quality, and resource sensitivity. Pressure information from existing climate vulnerability assessments (CVA) can inform the identification of relevant environmental variables (E), while sensitivity information from CVA may be used in resource sensitivity evaluation. CCCA implementation may be triggered by any evidence of departure from reference environmental conditions (anecdotal, empirical or mechanistic) and be the default for all strategic advice. For tactical advice, the decision to implement CCCA may be based on resource sensitivity evaluation and data quality/availability. High sensitivity may automatically trigger CCCA implementation, notwithstanding data quality. Moderate or low sensitivity may lead to CCCA implementation if based on high to moderate data quality. If the evidence of departure from reference environmental conditions is anecdotal and resource sensitivity is low or moderate and based on low data quality, there may be insufficient information and evidence to implement CCCA. In such cases, the need for data and knowledge augmentation could be clearly stated in the advice.

6. ADVICE DOMAINS MOST LIKELY TO BE IMPACTED BY CLIMATE CHANGE CONSIDERATIONS

Stock assessment advice in practice is most often developed for the provision of tactical advice. The uncertainties in stock assessment at this scale usually centre around two components of productivity, recruitment and mortality. Both of these factors are usually strongly influenced by local conditions at time scales of < 1 year. In such a case, it is unlikely that a climate change signal will be the predominant uncertainty. In addition, fisheries assessments for the most important stocks are usually repeated every 1-5 years, when data observations since the previous assessment are updated. For these reasons, **it is probably less likely than more that climate change conditioning for tactical fish stock assessment advice will be substantially different from reference or baseline advice, as long as the baselines are reviewed on appropriate time scales.** That proviso gives increased importance to recognising that strategic components of the advice are more likely to be affected by climate change. Consequently, climate change conditioning should still be considered in all cases where climate change effects are plausible to at least ensure that the baseline or reference benchmarks remain sound, and/or be reviewed on time scales relevant to the stock biology and environmental changes. Advice in other areas of the department (Table 1) are often focused more on strategic objectives or making one-off decisions that are hardly reversible, and consequently more likely to require climate change conditioning of their risk profiles for advice.

The more strategic aspects of stock assessment risk-based advice are where climate change considerations may be usefully included, even if CCF are not considered necessary in shorter term tactical advice. The precautionary approach framework (DFO 2006) has limit reference points, upper stock reference points, an implicit target and a harvest control rule. All these reference points are areas where climate change may be more likely considered, including the upper stock reference point and target reference points. For example, if a stock is recovering towards a target with a proposed time frame of 10-15 years, that target was set based on strategic considerations and the time to recovery set based on the assumption of stable stock productivity dynamics, and thus a stable environment. Climate change may be important at decadal time scales, and the risk estimates at such timescales need to take climate change impacts into account. This could be done through appropriate changes to the risk profile of the stock actually following the recovery trajectory, through adjusting the target and/or time to achieve it, or some combination of those strategic actions. The upper stock reference point may also be an area where climate change considerations could change the target level, even for stocks currently in the healthy zone. Whether the climate is becoming more or less favourable for the stock, so yield targets like Bmsy could be higher or lower, and more or less likely to be achieved for population dynamics reasons, even if the fishery remains well managed in terms of exploitation rate.

Another area of stock assessment advice where climate change considerations may be included would be in simulation work such as MSE. The base operating model (process-based model on stock dynamics) used in MSE generally represents present conditions based on fitting model parameters to fishery datasets. The fishing strategy developed in an MSE is tested against the operating model conditions but it is useful to have alternative operating models with varying degrees of plausibility in order to test the efficacy of fishing strategies under the range of plausibility. If strategies are meant to work under a variety of conditions and for a relatively long time, then alternative operating models which incorporate climate change signals could be useful stress tests for an MSE. It will remain up to the participants and scientists involved in the particular MSE process to decide how important it will be to adopt a climate change-conditioned management procedure or consider management procedures that are robust to climate change and tested through operating models that account for climate change.

7. SUMMARY

With the current rate of climate change impacting Canada’s aquatic environment, it is no longer acceptable to assume that previous levels of fish production or healthy and critical states will remain in perpetuity. A strategy for developing climate change conditioned advice is therefore an important addition to fish stock assessment, and similar strategies are likely to soon become an important consideration for other Sectors in the department where risk-based advice for biological resource management is required.

Advice in the department is often provided for short term tactical reasons, particularly for harvest management, but advice can also be longer term or strategic. Understanding the time frames of the advice is important for considering how climate change conditioning is likely to impact advice. Ironically, given that the present document focuses on climate impacts on stock assessment advice, tactical stock assessment advice is likely to be an area of management in the department less frequently affected directly by climate change. This is partially due to the short term nature of advice on stock status and annual harvest, and partly to the codification of the stock assessment advisory process which already schedules regular updates to the assessment methods and benchmarks, often several times within the generation time of the stock being managed. The repeated analysis of stock status and trend does build in some adaptation to changing environment through the update cycle. This is not universal however, for example, when the assessment update frequency is near the generation time of the stock or when an E variable is changing very quickly owing to non-linearities and threshold effects of climate impacts. Strategic components of stock assessment advice such as some kinds of reference points or long term management strategies are, however, more likely to require climate change conditioning, to address the additional uncertainties that a changing climate introduce to assessment and management.

Science advice for biological resource management in the Department is risk-based regardless of whether or not that risk is known or stated explicitly. This means that conditioning risk of decisions to climate change hypotheses becomes an operational means of considering climate change over multiple sectors. The risk profiles for decisions in fish stock assessment under climate change have been explored here but this approach could equally be applied for different sectors and also for any factor which potentially alters the risk field (e.g., ecosystem changes). In data rich cases, for example stock assessment with a process-based model, developing risk profiles is tractable, although usually not simple. With plausible hypotheses about climate change impacts on a stock’s production and/or dynamics, it becomes relatively straightforward to condition the risk profiles (and the advice) to climate change. Most fish stocks and other biological resources managed by the department do not have mechanistic models allowing full development of risk profiles. In situations with poor process knowledge and/or limited data, semi-quantitative or categorical climate conditioning factors (CCFs) can be developed to deliver climate change conditioned advice until data and process knowledge are augmented. This approach is a means of adjusting the “standard” advice, which should account for changes in productivity and risk of achieving objectives owing to other factors such as data quality or climate change.

Developing climate change conditioning factors should be an area of more focused research over the next several years. Workload would be reduced if these conditioning factors could be available for classes of stocks and would link with the hypothesised degree of change in environmental variables caused by climate change, and both of these avenues should be explored.

Further exploration of appropriate environmental variables for a stock that align with the nature of the advice required will contribute to improving climate conditioned advice. Climate vulnerability assessments (CVA) have already been developed for many species and stocks managed by the Department and this work forms a pool of knowledge which can be drawn upon for developing climate change conditioning of the advice. Future work on developing climate conditioned advice in the Department should consider work already conducted on incorporating external variables in stock assessments (Pepin et al. 2018), species vulnerability assessments and climate conditioning factors.

8. NEXT STEPS

This document lays the foundation of a risk-based strategy to incorporate environmental variation and climate change in the formulation of scientific advice relating to biological resource management in the Department. Operationalising this strategy in a number of case study examples will be an obvious and important next step. We identify the followings as priority work required to test, validate and fully operationalise the strategy:

1. Sensitivity assessment of fisheries management strategies already in place, to alternative E/E_{base} specifications.
2. Demonstration and implementation of the strategy in data-limited examples including the definition of climate conditioning factors (CCFs) based on life history data, empirical information derived from experimental studies, or expert knowledge.
3. Performance assessment of CCFs using information from data-rich systems in which at least partial process understanding of resource dynamics response to E/E_{base} is available.
4. Working with clients of the advice (both departmental and external) on defining a set of rules for CCCA, including advice components and recommendations associated with different CCFs and their frequency of occurrence over time.
5. Simulation testing of CCFs and their consequence on CCCA and fisheries.

9. REFERENCES CITED

A'mar, Z.T., Punt, A.E. and Dorn, M.W. 2009. The impact of regime shifts on the performance of management strategies for the Gulf of Alaska Walleye Pollock (*Theragra chalcogramma*) fishery. Canadian Journal of Fisheries and Aquatic Sciences 66, 2222–2242.

Auger-Méthé, M., Field, C., Albertsen, C.M., Derocher, A.E., Lewis, M.A., Jonsen, I.D. and Flemming, J.M. 2016. State-space models' dirty little secrets: even simple linear Gaussian models can have estimation problems. Nature Scientific Reports, 6: 26677.

Bojinski, S., Verstraete, M., Petersen, T.C., Richter, C., Simmons, A. and Zemp, M. 2014. The concept of essential climate variables in support of climate research, applications and policy. Bulletin of the American Meteorological Society 95: 1431-1443.

Brunel, T., Piet, G.J., van Hal, R. and Rockmann, C. 2010 Performance of harvest control rules in a variable environment. ICES Journal of Marine Science 67, 1051–1062.

Busch, D.S., Griffis, R., Link, J., Abrams, K., Baker, J., Brainard, R.E., Ford, M., Hare, J.A., Himes-Cornell, A., Hollowed, A., Mantua, N.J., McClatchie, S., McClure, M., Nelson, M.W., Osgood, K., Peterson, J.O., Rust, M., Saba, V., Sigler, M.F., Sykora-Bodie, S., Toole, C., Thunberg, E., Waples, R.S. and Merrick, R. 2016. Climate science strategy of the US National Marine Fisheries Service. Marine Policy 74, 58-67.

De Oliveira, J.A.A. and Butterworth, D.S. 2005. Limits to the use of environmental indices to reduce risk and/ or increase yield in the South African anchovy fishery. African Journal of Marine Science 27, 191–203.

Deyle, E.R., Fogarty, M., Hsieh, C. Kaufman, L., MacCall, A.D., Munch, S.B., Perretti, C.T, Ye,H. and G. Sugihara. 2013. Predicting climate effects on Pacific sardine. Proceedings of the National Academy of Sciences of the United States of America 110(16): 6430–6435.

DFO. 2006. A Harvest Strategy Compliant with the Precautionary Approach (PDF). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2006/023.

DFO. 2012. Proceedings of the National Workshop for Technical Expertise in Stock Assessment (TESA): Maximum Sustainable Yield (MSY) Reference Points and the Precautionary Approach when Productivity Varies; December 13-15, 2011. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2012/055.

DFO. 2013a. Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Pacific Large Aquatic Basin. DFO Can. Sci. Advis. Sec. Sci. Resp. 2013/016.

DFO. 2013b. Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Arctic Large Aquatic Basin. DFO Can. Sci. Advis. Sec. Sci. Resp. 2012/042.

DFO. 2013c. Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada's mandate - Atlantic Large Aquatic Basin. DFO Can. Sci. Advis. Sec. Sci. Resp. 2012/044.

DFO. 2013d. Risk-based assessment of climate change impacts and risks on the biological systems and infrastructure within Fisheries and Oceans Canada’s mandate – Freshwater Large Aquatic Basin. DFO Can. Sci. Advis. Sec. Sci. Resp. 2013/011.

FAO. 1996. Precautionary approach to fisheries. Part 2: scientific papers. Prepared for the Technical Consultation on the Precautionary Approach to Capture Fisheries (Including Species Introductions). Lysekil, Sweden, 6–13 June 1995. (A scientific meeting organized by the Government of Sweden in cooperation with FAO). FAO Fisheries Technical Paper. No. 350, Part 2. Rome, FAO. 1996. 210p.

FAO. 2016. Report of the Expert Meeting on Improving Progress Reporting and Working Towards Implementation of Aichi Biodiversity Target 6. FAO (Rome), SCBD (Montreal), IUCN-CEM-FEG (Brussels): 42 p.

Freon, P., Cury, P., Shannon, L. and Roy, C. 2005. Sustainable exploitation of small pelagic fish stocks challenged by environmental and ecosystem changes: a review. Bulletin of Marine Science 76, 385–462.

Fulton, E., Punt, A., Dichmont, C., Gorton, R., Sporcic, M., Dowling, N. ,Little, L., Haddon, M., Klaer, N., C. Smith, D. 2016. Developing risk equivalent data-rich and data-limited harvest strategies. Fisheries Research 183, doi.org/10.1016/j.fishres.2016.07.004

Fulton, E.A., Punt, A.E., Dichmont, C.M., Gorton, R., Sporcic, M., Dowling, N., Little, L.R., Haddon, M., Klaer, N. and Smith, D.C. 2016. Developing risk equivalent data-rich and data-limited harvest strategies. Fisheries Research. 183: 574-587.

Garcia, S.M. and Rice, J. 2018. Aichi biodiversity target 6: scientific assessment of progress towards target 6. IUCN-CEM-FEG. 57 pp.

Gjøsæter, H., Bogstad, B., Tjelmeland, S. and Subbey, S. 2014. A retrospective evaluation of the Barents Sea capelin management advice. Marine Biology Research 11, 135–143.

Henson, S.A., Beaulieu, C., Ilyina, T., John, J.G., Long, M., Séférian, R., Tjiputra, J. and Sarmiento, J.L. 2017. Rapid emergence of climate change in environmental drivers of marine ecosystems. Nature Communications doi.org/10.1038/ncomms14682

Hilborn, R. (2012) The evolution of quantitative marine fisheries management 1985-2010. Natural Resource Modeling 25, 122-144

Hollowed, A.B., Barange, M., Beamish, R.J., Brander, K., Cochrane, K., Drinkwater, K., Foreman, M.G.G., Hare, J.A., Holt, J., Ito, S.-I., Kim, S., King, J.R., Loeng, H., MacKenzie, B.R., Mueter, F.J., Okey, T.A., Peck. M.A., Radchenko, V.I., Rice, J.C., Schirripa, M.J., Yatsu, A. and Yamanaka, Y. 2013. Projected impacts of climate change on marine fish and fisheries. ICES Journal of Marine Science 70, 1023-1037 doi.org/10.1093/icesjms/fst081.

ICES. 2017. Report of the ICES/PICES Workshop on Regional climate change vulnerability assessment for the large marine ecosystems of the northern hemisphere (WKSICCME-CVA), 19-22 July 2017, ICES Headquarters, Copenhagen, Denmark. ICES CM 2017/SSGEPD:23. 67pp.

Landres, PB, Morgan, P, Swanson FJ. 1999. Overview of the use of natural variability concepts in managing ecological systems. Ecological Applications 9:1179-1188.

Nadeau, C.P. and Fuller, A.K. 2015. Acounting for multiple climate components when estimating climate change exposure and velocity. Methods in Ecology and Evolution 6, 697–705.

Pepin, P., King, J. Holt, C., Gurney-Smith, H., Shackell, N., Hedges, K., Bundy, A. 2020. Incorporating climate, oceanographic and ecological change considerations into population assessments: A review of Fisheries and Oceans Canada's science advisory process. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/043. In press.

Pörtner, H.-O., Karl, D.M., Boyd P.W., Cheung W.W.L., Lluch-Cota S.E., Nojiri Y., Schmidt D.N. and Zavialov, P.O. 2014: Ocean systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L.White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411-484.

Punt, A.E., A'mar, T., Bond, N.A., Butterworth, D.S., de Moor, C.L., De Oliveira, J.A.A., Haltuch, M.A., Hollowed, A.B. and Szuwalski, C. 2013. Fisheries management under climate and environmental uncertainty: control rules and performance simulation. ICES Journal of Marine Science 71, 2208–2220

Punt, A.E., Siddeek, M. S. M., Garber-Yonts, B., Dalton, M., Rugolo, L., Stram, D., Turnock, B.J. and Zheng, J. 2012. Evaluating the impact of buffers to account for scientific uncertainty when setting TACs: application to red king crab in Bristol Bay, Alaska. ICES Journal of Marine Science 69, 624- 634,

Scholander, P.F., Hock, R., Walters, V., Johnson, F. & Irving, L. 1950. Heat regulation in some arctic and tropical mammals and birds. Biological Bulletin 99, 237–258.

Sugihara, G., May, R., Ye, H., Hsieh, C.H., Deyle, E., Fogarty, M. and Munch, S. 2012. Detecting causality in complex ecosystems. Science, 1227079.

Tommasi, D., Stock, C.A., Hobday, A.J., Methot, R., Kaplan, I.C., Eveson, J.P., Holsman, K., Miller, T.J., Gaichas, S., Gehlen, M., Pershing, A., Veclimate changehi, G.A., Msadek, R., Delworth, T., Eakin, C.M., Haltuch, M.A., Séférian, R., Spillman, C.M., Hartog, J.R., Siedlecki, S., Samhouri, J.F., Muhling, B., Asch, R.G., Pinsky, M.L., Saba, V.S., Kapnick, S.B., Gaitan, C.F., Rykaczewski, R.R., Alexander, M.A., Xue, Y., Pegion, K.V., Lynch, P., Payne, M.R., Kristiansen, T., Lehodey, P., Werner, F.E. 2017. Managing living marine resources in a dynamic environment: The role of seasonal to decadal climate forecasts. Progress in Oceanography 152, 15-49.

World Meteorological Organization. (2018, April 18) Essential Climate Variables.

APPENDICES

ANNEX A: A RISK STRATEGY FOR INCORPORATING CLIMATE CHANGE INTO STOCK ASSESSMENT: A DATA AND PROCESS-KNOWLEDGE RICH EXAMPLE

The following presents an example for a stock assessment where an analytical model has been fitted to the stock. This model fitting provides estimates of stock productivity parameters their variances. Reference points can be calculated from the model fitting. The model can be projected forward and the probability of the stock biomass being at or above a reference point given a particular fishing rate can be determined.

The climate conditioning is done by comparing risks associated with not achieving an objective in a certain period of time under reference conditions, and comparing the same risk under climate changed conditions. They key part of this example is that process knowledge of the climate variable on the fish productivity process is known or assumed. The climate conditioned equivalent risk advice is then how much fishing needs to be changed (up or down) to achieve the management objective in the same period of time at the same level of risk.

The population model

A Bayesian surplus production model fitted to a relatively low productivity cold-water adapted groundfish stock. The specifics of the model fitting do not matter for present purposes simply that we have applied a method which fits data based on past conditions (baseline conditions), then projects probability of achieving an objective for stock state in the future under this baseline conditioning. The groundfish stock chosen is at the southern end of its range and therefore it is known that increased temperatures caused by climate change should negatively influence stock production. The input data for this stock and temperature extend back to 1990 and this data series can be used to determine not only baseline production but also reference points and impacts of climate on production.

The climate conditioning of the advice is the conditioning of risk of not achieving an objective under a climate changed productivity regime and how to manage the fishing activity to maintain probability of achieving the advice.

Productivity dependence on environment

Ideally, there is process knowledge or at least a statistical basis for relating stock productivity (P) to the environment (E). This could enter the model projection in many ways. It may be a simple change in P as a function of E from the start of a projection. E may gradually change over a time period and this time dependence would be included. E could also differentially affect sub parameters of P. For example it may affect growth differently than it does recruitment or natural mortality. We assume that the stock assessors have the best knowledge to know how to model impacts of E on P, the point being simply that there is a relationship between E and P that can be specified.

In the present example, we have assumed that the intrinsic rate of growth is a function of mean ambient water temperature. This can be is expressed essentially as an anomaly from past conditions as a simple ratio of the mean historic temperature to data period used in fitting the model. A production model parameterisation is convenient because it subsumes many productivity process however it should be noted that this can also be a weakness depending on how E affects different components of E.

Risk equivalence

Risk equivalence is the concept of maintaining the same level of risk for a management decision on not achieving an objective regardless of method (Fulton 2016). Risk equivalence can however also be applied to maintaining risk levels in management decisions when productivity of a stock changes. For example if a stock becomes more productive than it was previously, it could support a greater catch level while maintaining the same level of risk of not achieving an objective (SSB falling below B_{target} or B_{pa}). We are using risk equivalence in this manner in terms of climate change impacts on stock productivity.

This is a slightly different use of the term because we are concerned with adjusting management measures to align with productivity regime changes rather than trying to align management measures to give similar actions in the face of different levels of data deficiency. We could conceivably consider these different axes of risk equivalency.

Axes of risk equivalency

Risk equivalency in Australia is primarily to achieve consistent application of risk of not achieving objectives when the methods of calculating risk differ because of assessment methods applied. Another axis of risk equivalency is the consistent application of risk when new factors are affecting stock productivity. The equivalency in risk in the latter case is not striving to create equivalency in the same historical period but equivalency between the past period and a future period when a factor such as climate change will affect a stock's productivity in the future.

Fig A1.1 shows a baseline scenario for a stock and four other scenarios related to long term temperature change. Since B_{msy} is a target but assessments are uncertain and a well-managed stock still varies around its target due to random variation in many biological factors, there is an implicit risk of 50% of being above or below that point, under successful management. The logistic curve F's at 0.5 probability are therefore depicted as the vertical lines for each scenario. The risk equivalent fishing strategy given long term temperature means can be considered the difference between the climate change curve and the baseline curve F at 0.5 probability. So for the warmest scenario the F50 is 0.034 while for the baseline it is about 0.157. This means that for the warmest temperature scenario, the fishing mortality applied to the stock is five times less than baseline to achieve the same probability of achieving B_{msy} at the end of 10 years. Thus the consistent application of risk under this temperature change scenario would allow only limited fishing.

Also note that because the curves in figure A1.1 show the full (inverse) cumulative probability distribution of achieving the objective (high probability of success at F = 0, declining as F increases. This allows the approach to be used in cases where even under zero fishing the stock may still fail to achieve the status consistent with the objective (perhaps $B >= B_{msy}$, when the stock has been overfished in the past and not fully recovered), by simply having the Y value at the X intercept be some value less than 1.0 (perhaps 0.65, reflecting a 65% chance of $B = B_{msy}$ with no fishing), and the curves still delving systematically as F is hypothesised to increase. Also if there is knowledge that some of the relationships involving in estimating the risk profile are skewed or platykurtic, the two arms of the probability density function around its central moment do not have to be symmetrical. The curvature of the arms can differ in whatever ways the information supports, and that knowledge can be transferred directly into the risk estimates.

The simple process knowledge of E on P injected into this data rich example (eq 1) allows a clear application of risk equivalent climate conditioned advice. In most cases however, neither the baseline risk curve can be developed so clearly nor will there be such perfect knowledge of process of E on P; nevertheless, conceptually the same ideas would be behind any application. That is, there is a baseline P, there is an objective for the stock and there is an activity which can be controlled (WUAF). The probability of achieving an objective is a function of P and WUAF. Climate change then affects P and in order to maintain the same probability of achieving the object the level of WUAF must change. Particularly with increasingly imperfect and/or incomplete information, some systematic way of using the available information is essential If there is to be any chance of developing risk-based advice in a consistent and transparent manner. We therefore need to develop rules of thumb for (1) determining the baseline probability of achieving the objective for a WUAF (2) how to change the probability as a function of the climate change impact on P.

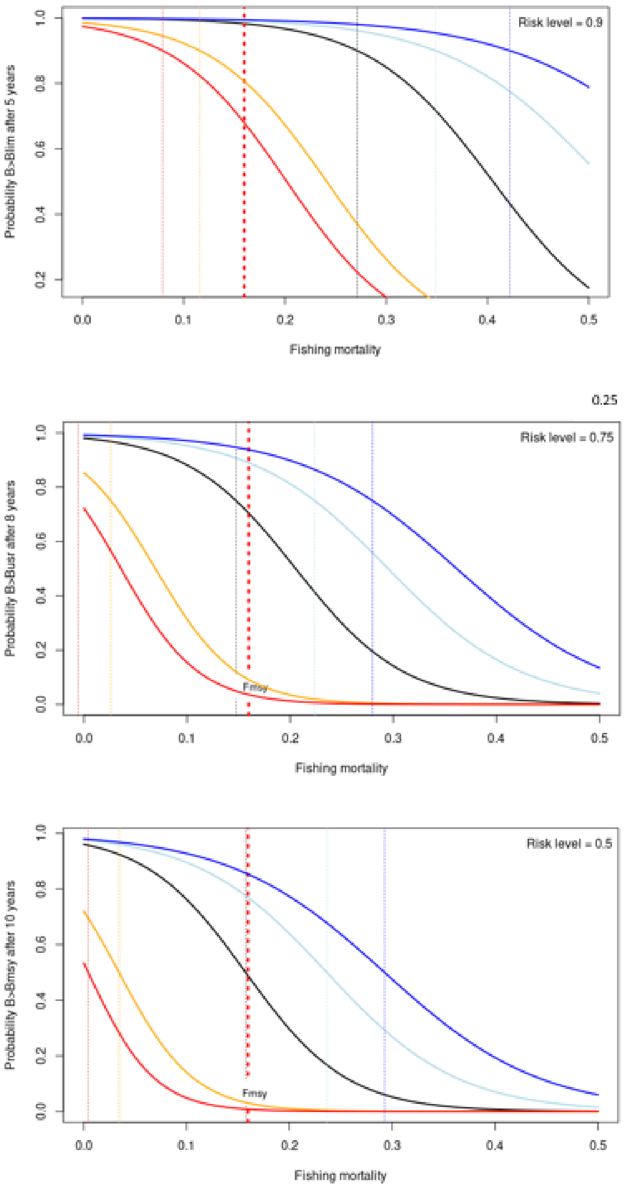

Figure A1.1: probability of a stock achieving a reference point where the stock growth rate is influenced by an external climate variable (temperature). The red curve being the warmest temperature, blue the coldest and black the baseline temperature. Fmsy for the baseline scenario is shown on the graph as the thick dashed vertical line. F_{msy} is a common fishing mortality reference that should not be exceeded. Risk equivalent F values under different temperature regimes are shown by their corresponding coloured vertical lines.

The risk equivalent advice for fishing in order to meet an objective is shown in Table A1.1. For example the baseline (temperature 5.2 C) fishing mortality advice for getting the biomass above the upper stock reference point (B>B_{usr}) in 8 years. This will correspond to a specific catch each year over the projection period. However, if the bottom temperature warms to 5.33 C for the whole 8 year projection period than the fishing mortality advice given the same objective and same amount of time to achieve it would a more than 6-fold decrease from the baseline to 0.023.

Table A1.1: Risk equivalent F levels for achieving some common fisheries objectives under different climate conditions characterised by bottom temperature. This is the result of projecting from the joint posterior of Bayesian biomass production model fitted to cold water seeking groundfish and inferring a causal relationship between temperature and the intrinsic rate of growth as a multiplier of it.

Temperature	**Objective**	**Time to achieve objective (years)**	**Acceptable risk of not achieving objective**	**F**
Baseline (5.20 C)	B>B_{lim}	5	0.1	0.267
Cold (5.00 C)	B>B_{lim}	5	0.1	0.357
Very cold (4.55 C)	B>B_{lim}	5	0.1	0.413
Warm (5.33 C)	B>B_{lim}	5	0.1	0.121
Very warm (5.66 C)	B>B_{lim}	5	0.1	0.077
Baseline (5.20 C)	B>B_{usr}	8	0.25	0.148
Cold (5.00 C)	B>B_{usr}	8	0.25	0.227
Very cold (4.55 C)	B>B_{usr}	8	0.25	0.285
Warm (5.33 C)	B>B_{usr}	8	0.25	0.023
Very warm (5.66 C)	B>B_{usr}	8	0.25	0.000
Baseline (5.20 C)	B>B_{msy}	10	0.5	0.157
Cold (5.00 C)	B>B_{msy}	10	0.5	0.236
Very cold (4.55 C)	B>B_{msy}	10	0.5	0.293
Warm (5.33 C)	B>B_{msy}	10	0.5	0.034
Very warm (5.66 C)	B>B_{msy}	10	0.5	0.004

This data rich example shows how catch (or fishing mortality) options can be provided to managers which could be considered climate conditioned. There are multiple plausible scenarios that could be developed to reflect this climate conditioning and the simple one chosen here as an abrupt productivity regime shift may not be the most plausible.

ANNEX B: A RISK STRATEGY FOR INCORPORATING CLIMATE CHANGE INTO STOCK ASSESSMENT: A DATA AND PROCESS-KNOWLEDGE MODERATE EXAMPLE

A cold water adapted data poor groundfish stock in a warming environment is the focus of this particular example. It is assumed that there is a relative abundance index, an annual catch time series and annual measurements of an environmental variable that impacts stock productivity and also which is assumed reflects climate change. There is no fitted analytical model for the stock; however a model is derived based on separating the natural components of production from fishing and then assuming a causal relationship between those natural productivity components and an environmental variable. The data used for this method is widely available data for a large number of DFO managed species.

Derivation of a climate-dependent production relationship

The simplest means of determining stock productivity is the starting basis:

$${}^{g}P_t = R_t + G_t + ND_t + C_t \qquad \text{eq. 1}$$

Where the gross production over the year t (${}^{g}P_t$) is equal to the biomass recruitment over t (R_t) added to the mean biomass growth of all individuals over time t (G_t), added to the biomass loss due to natural death (non fishing) (ND_t) added to the catch biomass over the period (C_t). This is the simplest form of biomass accounting over time in fisheries.

The net production (${}^{n}P_t$) is the sum total of gains (R_t and G_t) less the losses (NDt and C_t) and can be estimated from data as the biomass (B_t) at the start of one period minus the biomass as the start of the previous period:

$${}^{n}P_t = R_t + G_t + ND_t - C_t = B_{t+1} - B_t = \Delta B \qquad \text{eq. 2}$$

We can further rearrange this equation such that natural processes affecting production are separated from human induced ones (fishing):

$${}^{n}P_t = \Delta B + C_t = R_t + G_t + ND_t \qquad \text{eq. 3}$$

Showing that ΔB as a measure of net production added to the catch is equal to the sum total of the other natural productivity components. We term this new quantity net natural production (${}^{n}NP_t$) and we have estimates of all the variables on the left side of the equation if there is a biomass index time series and catch reporting.

The natural productivity components recruitment, growth and natural mortality are considered to be a function of two factors, the biomass of the stock at time t and external environmental or ecosystem variables:

$${}^{n}P_t = f(B_t, E_t) \qquad \text{eq. 4}$$

Where E_t is considered to be an environmental forcing variable on production. Since we have an annual estimate of B_t in this situation, we can standardise the production by that biomass to get a specific rate of net natural production which is then purely a function of an environmental variable.

$$\frac{{}^{n}P_t}{B_t} = f(E_t) \qquad \text{eq. 5}$$

In subsequent text, ${}^{N}P/B$ is simply referred to a P/B. In the present example it is considered a linear relationship but it could be any kind of non-linear relationship. Quadratic may be a useful relationship because it reflects an environmental optimum for a production process.

This fitted relationship is then used to predict how stock production will change with the environmental variable by projecting from the last data year and with catch and a climate prediction provided. It is steady state assumption which relates all productivity processes to the environmental forcer in a year it is therefore unlikely to be useful as a biomass predictor for short term advice but it is useful to show directionality of the production process under climate change and how this could trade-off with catch.

Data required:

- A survey biomass time of the recruited and reproducing population
- A total landings time series
- An environmental index time series
- These series correspond in time for some years

Assumptions:

- The survey is a representative sample of the recruited and reproducing population
- The catch series represents total fishing mortality on the stock
- Survey catchability is known or informed by expert knowledge (e.g., 0.5)
- There is no density dependence in the productivity process

Other inputs:

- Definition of a reference period e.g., a series of years when catches were considered adequate and relatively stable and the survey index was also relatively stable. This is not strictly necessary to do any projection but this is used to define a reference point, i.e. an objective. If one is unwilling to define an objective, then stock management is by definition ad hoc and it does not really matter if climate change is occurring or not since there no management objective.
- A projection for the variable affecting production which reflects climate change.
- A future catch scenario.

Outputs:

This relationship can be projected indefinitely. What should be examined with this is to determine how long it would take to achieve an objective given catch levels and the level of environmental change. This is deterministic and it assumes the median is correct therefore if it took five years to achieve the objective under status quo catch with the environmental signal it is actually a 50% probability of achieving that objective in five years. This is appropriate for a target but not a limit reference point for example. A better procedure would be to perform the projection with uncertainty. The uncertainties that would enter would be the projected environmental signal, the uncertainty in the environment to stock production relationship and the catchability of the survey.

The worked example

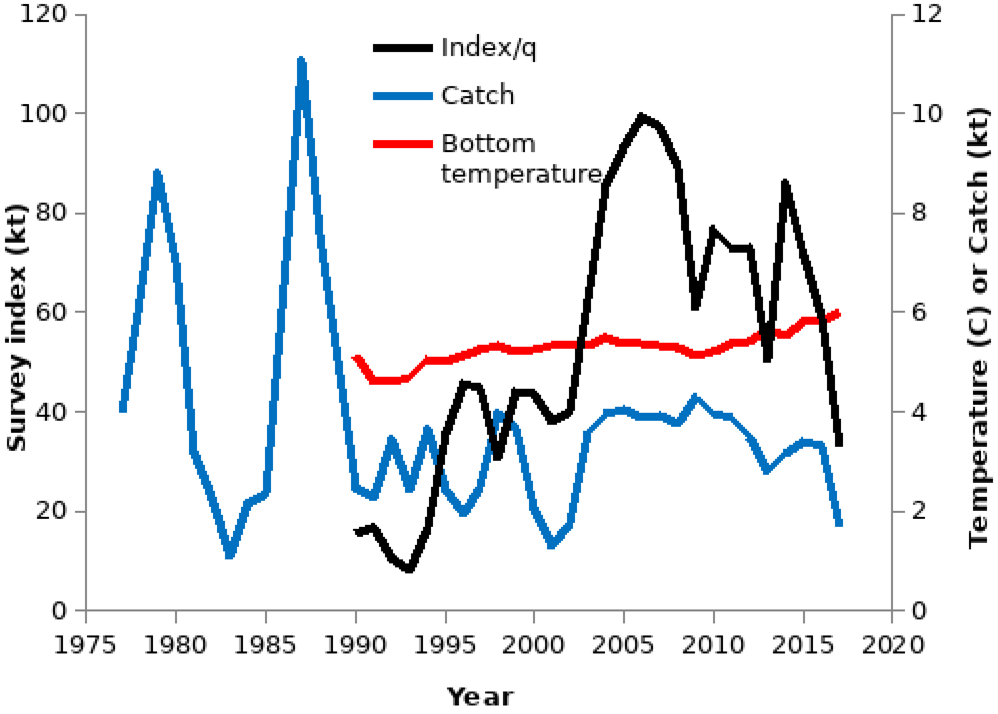

Figure A2.1: projected stock biomass (2018 on) under reference period catch and one realisation of randomly sampled temperature from the five most recent data years (2013-2017). The horizontal line is the reference period index biomass which is considered a target. The vertical line marks the start of the projection.

The survey catch index (Fig A2.1) is considered a good relative biomass index for this stock. The biomass is expressed as kt swept area biomass and is considered a minimum trawable biomass estimate. To do P/B calculation, catch needs to be included and therefore the survey biomass estimate should be bumped to the theoretical absolute estimate to put it on the same scale as catch. In this case, it was assumed that q=0.5, i.e. the survey underestimates the actual stock biomass by 50%. This is not strictly necessary because P/B is a relative measure of production but if the survey index is of a much smaller magnitude than catch, catch will dominate in the numerator and the goal is to make these scaling factors in the numerator and denominator cancel each other, therefore a q that roughly puts the catch and survey index on the same scale should be considered.

The temperature signal appears relatively flat but it is bottom water temperature in a deep channel which does not vary much and small changes can affect production. The warmer the bottom water, the worse it is for production of this species. Temperature is a variable that brings in other aspects such as hypoxia as warmer bottom water is associated with more hypoxia. Warmer temperatures can be positive for other competitor species and this enhances the impact of temperature but on other aspects of production. Also a small bottom water change in temperature often signals a larger change in sea surface temperature that may be much more significant for other components of the system affecting this stock.

Despite the small change in bottom water temperature, there is a weak impact of temperature on NP/B (Fig. A2.2).

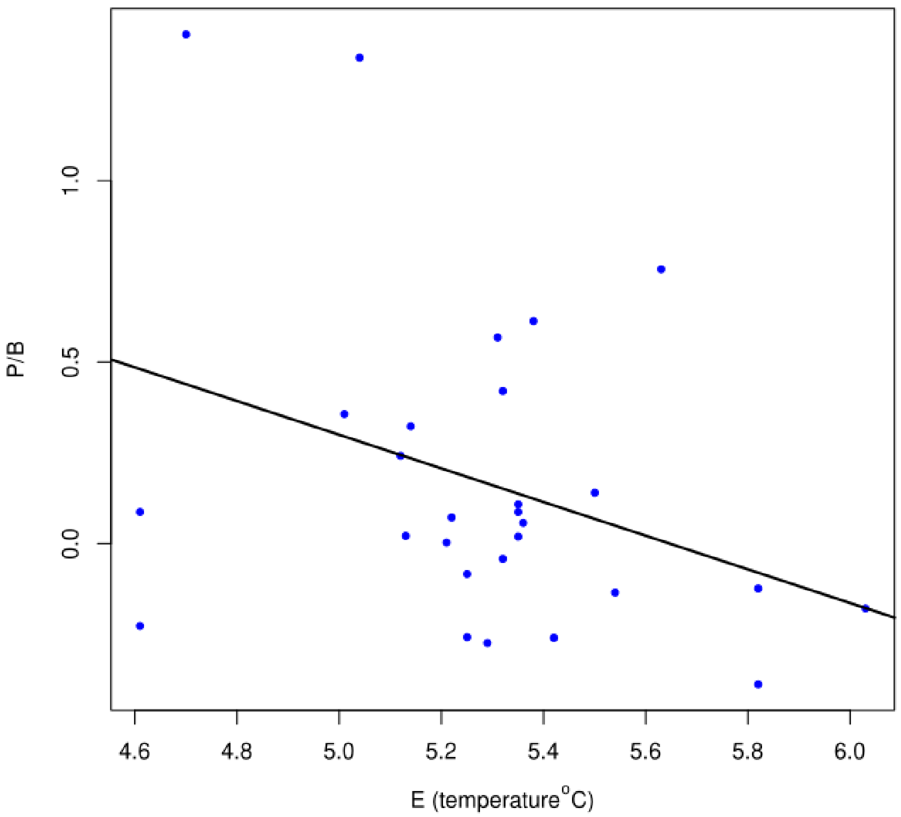

Figure A2.2: the NP/B vs bottom water temperature ratio for a groundfish stock. This assumes a survey catchability of 0.5 and that all fish killed were included in landings data.

The projection

The stock biomass was then projected into the future with a reference period catch assumption (2.545 kt/year) and assuming the bottom temperature reverted back to that in the reference period (5.2 C).

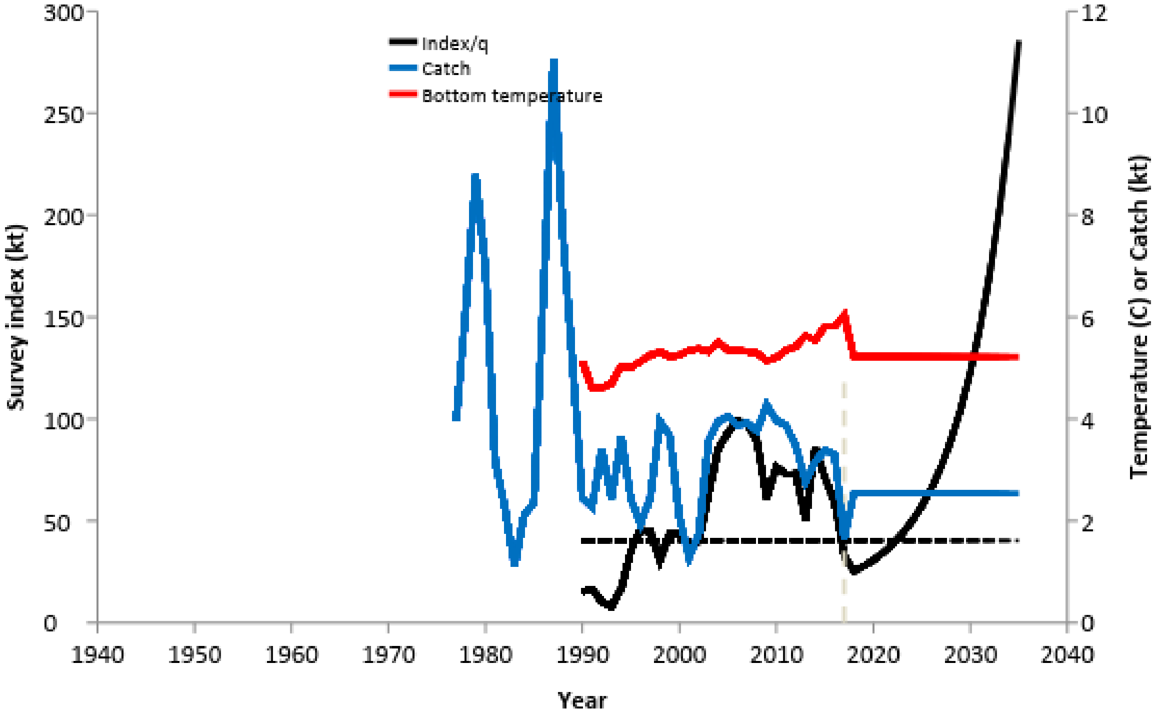

Figure A2.3: projected stock biomass (2018 on) under reference period catch and reference period temperature. The horizontal line is the reference period index biomass which is considered a target. The vertical line marks the start of the projection.

The projected biomass surpassed the target objective by 2022 under these catch and temperature assumptions. This is the ideal scenario where catches are low and the water cools to what would seem about an optimum level (Fig. A2.3).

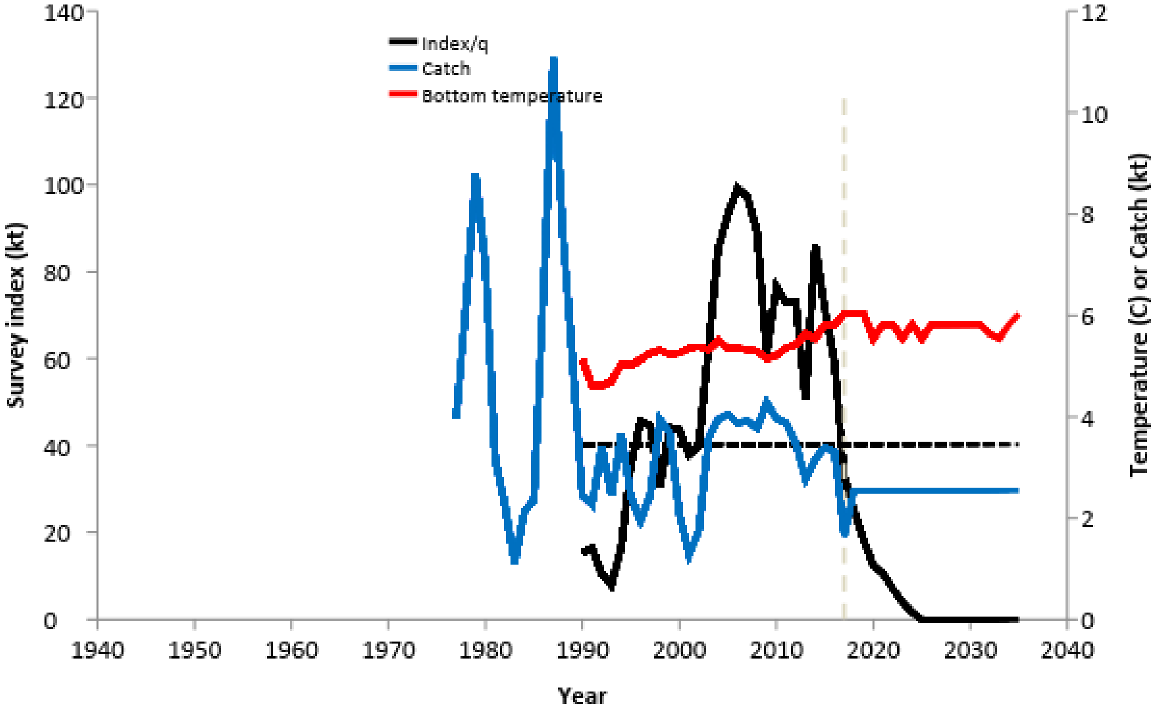

Figure A2.4: projected stock biomass (2018 on) under reference period catch and one realisation of randomly sampled temperature from the five most recent data years (2013-2017). The horizontal line is the reference period index biomass which is considered a target. The vertical line marks the start of the projection.

A projection with reference period catch and a single realisation of the temperature in the past five years (Fig A2.4) shows that stock is predicted to be extirpated by about 2025 under reference period catch level if the most recent temperature data remain over that period.

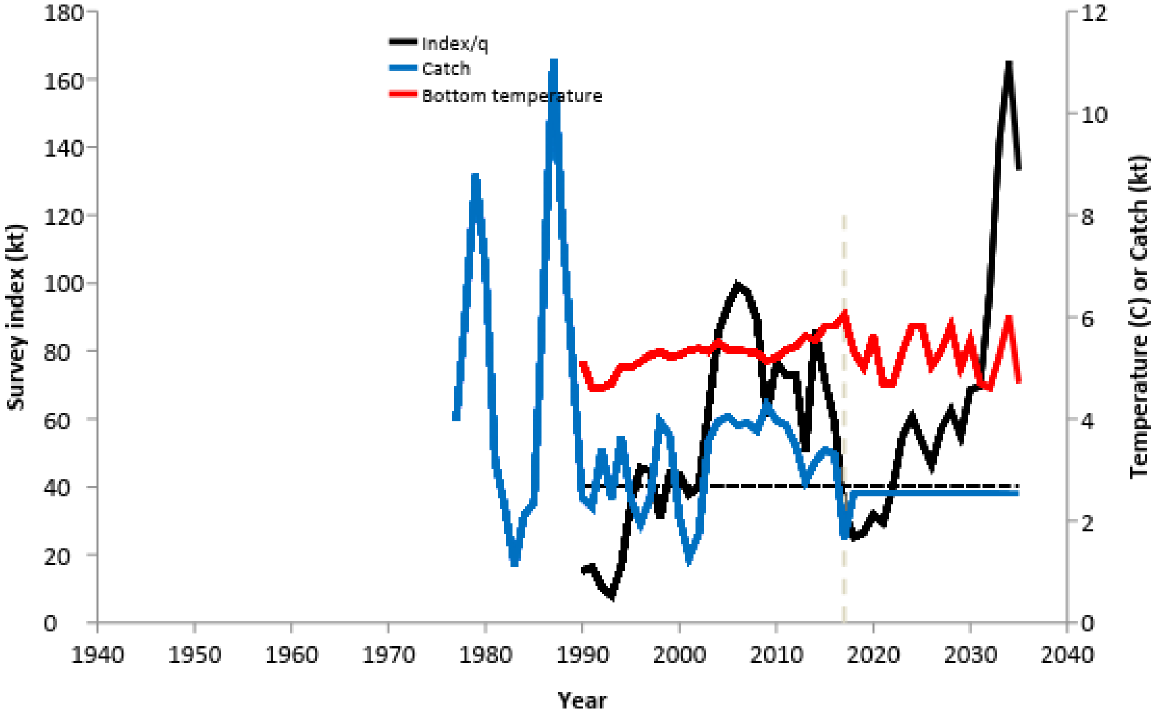

Figure A2.5: projected stock biomass (2018 on) under reference period catch and one realisation of randomly sampled temperature from the all data years (1990-2017). The horizontal line is the reference period index biomass which is considered a target. The vertical line marks the start of the projection.

A scenario where temperature going forward was randomly resampled from all those previously observed (Fig. A2.5) showed that biomass would increase considerable under reference period catch.

This simple projection can be done for any combination of catch and temperature and they trade off against each other which makes the climate change risk equivalent catch more apparent. The Kobe plots of these scenarios highlights the impacts of fishing under different climate scenarios in terms of defining safe operating zones for fishing (Fig. A2.6).

Climate change conditioned advice

With a target objective, time desired to reach it and a temperature projection for the future, one can determine the catch which will achieve this by this simple method. But if the goal and time remain the same then the only thing that can be altered to achieve the objective given the projected temperature is the allowable catch. Thus the risk equivalent advice under climate change is the TAC that will achieve the objective at the same time as the reference scenario. In some (most) realistic climate change scenarios (e.g., Temperature observed in the last five years) for this stock using this method, there is no TAC that will achieve the objectives – not even a moratorium. The advice under such a scenario might be to reduce TAC as low as possible and continue to monitor both the stock biomass and the temperature. If temperature continues to increase and stock biomass decrease for a repeated period of years then it would be wise to consider (1) changing the reference level (i.e. change the reference points) (2) prepare for effective commercial extirpation of the stock.

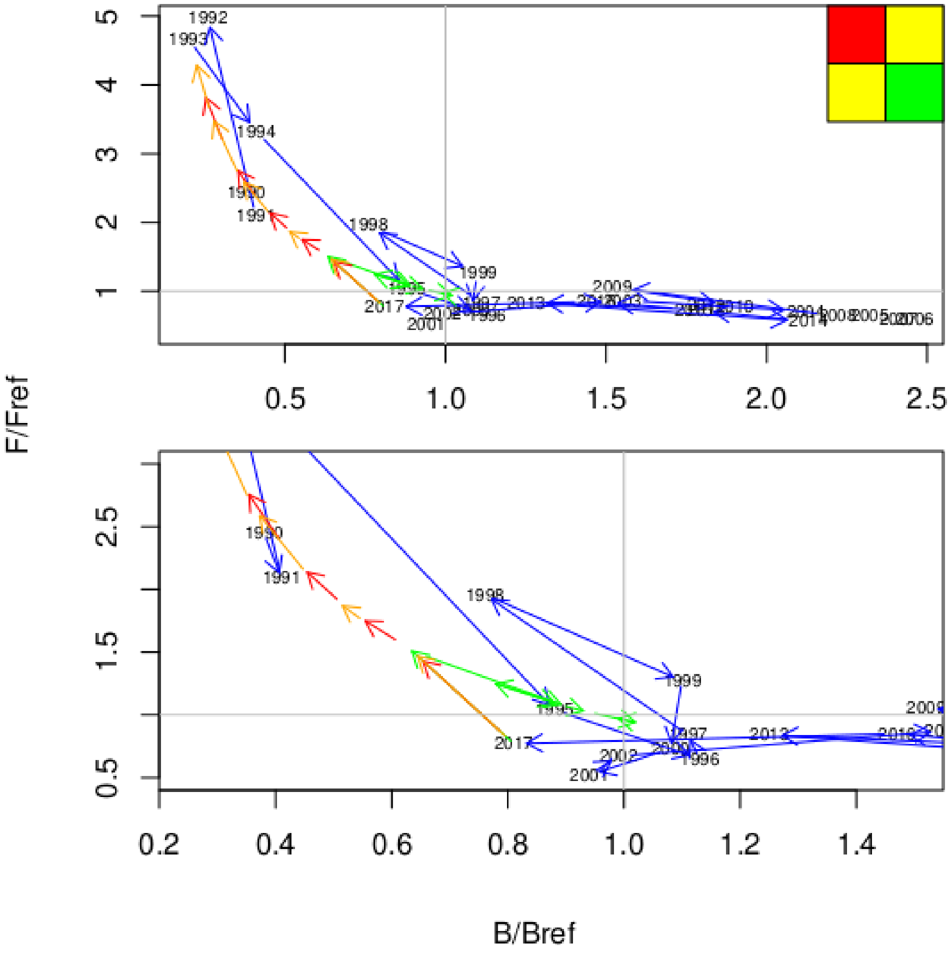

Figure A2.6: A Kobe plot with heat colour variable reflecting temperature showing the time series of the relative fishing mortality divided by the reference period fishing mortality and the relative biomass divided by the reference period biomass. The four zones represent risk zones where green is considered the safest zone while red is the worse. Three realisations of stock projections under climate change scenarios are depicted as red (increasing water temperature), orange (recent year water temperature) and green (cold water) arrows.

Summary

This data moderate makes assumptions about the variability of the production process for a stock but impact of some of those assumptions can be mitigated by including uncertainty going forward. This is relatively easy to code in R. Despite the fact that it is a population model assuming equilibrium production environment relationship, it has been derived from the simplest of assumptions and from data that are commonly available for many stocks managed by DFO. Methods like these have potential to offer climate conditioned stock exploitation advice.

How this could be used to impact advice during a RAP process

Fig A2.6 shows how including the climate variable (bottom temperature) in projections would affect the future stock state as depicted by the Kobe plot. That is, warmer temperatures show the stock going increasingly deeper into the red zone while cooler temperatures with status quo fishing can bring the stock back into the green zone. It would be incumbent upon the stock assessors and physical oceanographers at the RAP meeting for this stock to assign likelihoods to future climate scenarios and perform projections accordingly. If the goal is to move the stock into the green zone on the Kobe plot (management decision) then given the likelihood of a given climate projection, the stock assessor will need to determine the appropriate level of fishing reduction to achieve the management goal at a specified risk level under climate change.

References

Fulton, E., Punt, A., Dichmont, C., Gorton, R., Sporcic, M., Dowling, N., Little, L., Haddon, M., Klaer, N., Smith, D. 2016. Developing risk equivalent data-rich and data-limited harvest strategies. Fisheries Research. 183. 10.1016/j.fishres.2016.07.004.

ANNEX C: ENVIRONMENTAL CONDITIONING OF RISK: BASIS FOR A DATA-LIMITED EXAMPLE

The following concerns a hypothetical fishery resource (stock) for which data are insufficient and/or there is no accepted analytical model to quantify stock dynamics (and thus the response of the stock to harvest pressure or environmental change).

Available information

- A time series of commercial (fisheries-dependent) catch and catch-per-unit-effort (CPUE) relative abundance data.
- An agreed reference period for the stock (with corresponding reference levels for catch and relative abundance data).
- A set of management objectives (in this case: maintaining status quo = same catch as last few years)
- A time series of average annual temperature data.
- Life history attributes and related sensitivity scores.
- Results from old experimental studies suggesting a preferred temperature range for the stock.
- A decision matrix relating the magnitude of change in environmental state (E/E_{base}) and the level of confidence associated with the information available to the assessment and risk evaluation derived from reason presented in Fig 2 and Fig 3, main paper.

Approach

1. Calculate the risk of achieving the management objective in risk space considering uncertainty in the CPUE index (e.g., annual CV and normal distribution assumption) and various catch levels.
2. Estimate environmental state (e.g., temperature deviation from reference temperature values).
3. Estimate stock sensitivity to temperature change based on empirical life history and preferred temperature range information.
4. Multiple sensitivity estimates by corresponding score on decision matrix (weighting) and normalise to derive a semi-quantitative or categorical climate conditioning factor (CCF).
5. Environmentally condition the risk profile by multiplying standard risk values by the CCF
6. Ideally, advice should be based on a number of plausible scenarios resulting from different CCFs.

ANNEX D: DEFINITION OF TERMS

Climate change conditioned advice (CCCA): advice provided in the traditional manner for an activity (e.g., TAC level for a fish stock) but which has been conditioned for proposed climate change impacts over the temporal scales which the advice was supposed to stand. I.e. The risk inherent in the advice has been altered (or not) after an evaluation of the impacts of climate change on the risk.

Climate conditioning factors (CCF): Factors ranging that are multipliers of assessment advice (TAC, F) or possibly stock state estimates which account for climate change impacts on stock future productivity or state and which affect risk-based advice.

CRA: commercial, recreational or aboriginal fishery - directly from the Fisheries Act.

CVA: Species vulnerability analysis.

E: one or more environmental variables and associated values combined or separate which reflect climate change and affect the biological resource. E is always a quantitative time series.

[E]: A symbol used to represent the concept of stock external variables that affect the stock's productivity

E_{base}: a baseline value for an E variable that represents reference conditions for comparison of past and future stock states. E_t/E_{base} is sometimes used as a means of representing an environmental state at a particular time relative to the baseline state.

Reference condition: The biological or environmental conditions which characterise the model fitting period or reference period against which future states can be compared.

Risk equivalence: a strategy for ensuring that risk of not achieving an objective given a WUAF is similar given differences in data availability, process knowledge and changes in productivity of a biological resource resulting from climate change.

Risk profile: a general term to describe how the risk of not achieving an objective in a specified period of time changes with the intensity or scale of the WUAF. A risk profile may be explicit and can be depicted as a continuous curve or it may a remain conceptual link between risk of not achieving an objective or of experiencing a bad outcome that can be altered by managing a human activity.

WUA: work, undertaking or activity - directly from the Fisheries Act

WUAF: a term derived for this document which makes explicit the Fishery in WUA as possible harmful activity to resource status