FRAMEWORK FOR INCORPORATING CLIMATE-CHANGE CONSIDERATIONS INTO FISHERIES STOCK ASSESSMENTS

Context:

A key activity under the Department of Fisheries and Oceans Canada's Aquatic Climate Change Adaptation Services Program (ACCASP) is to advance understanding of the vulnerability of commercial species to the impacts of climate change and to develop a strategy to incorporate this knowledge into fisheries stock assessments.

To that end, a Canadian Science Advisory Secretariat (CSAS) peer review process was organized to develop a framework for the systematic integration of oceanographic/environmental climate change stressor data and fish stock vulnerability information into stock assessment advice in order to inform climate-ready decision making in fisheries resource management.

Previous climate change risk assessments conducted under ACCASP identified common risks and information needs associated with climate change across all DFO Regions. Similar biological risks across DFO Regions supports the usefulness of a common framework and climate-related tools to efficiently and effectively incorporate climate change into science advice. Identifying approaches and options that will remain biologically and socio-economically sustainable in the face of climate change is a critical need, as the best management decisions for Regions and their aquatic resources today will not necessarily be the best management decisions in the future under climate change.

This Science Advisory Report is from the May 8-9, 2018 meeting titled Framework for Incorporating Climate Change Considerations into Fisheries Stock Assessment. It presents the consensus outcomes from this process, which included multiple science inputs, and provides the departmental guidance under the Terms of References for this meeting. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- 178 DFO stock assessment documents, dating from 2000-2017 and including all taxonomic categories (anadromous, groundfish, invertebrates, pelagic, mammals, and elasmobranchs) from all DFO marine regions, were examined for their inclusion of climate-related material.
- 46% of the stock assessments described hypotheses or broad-scale conceptual linkages between climate, oceanographic or ecological variables and population dynamics. Analytical incorporation of these factors was lower, with quantitative incorporation in 21% and qualitative interpretation in 31% of assessments. Overall, 27% of assessments applied climate, oceanographic or ecological information in the provision of advice. However, these rates are considerably greater than the 2% of stock assessments worldwide which carried information on climate or environmental drivers all the way to tactical management decisions.
- Stock assessments of anadromous fishes, particularly Pacific salmon, consistently had the highest rates of including climate, oceanographic or ecological variables in the analyses, interpretation or provision of advice concerning stock status and forecasts; in contrast, elasmobranchs (sharks and rays) and marine mammals typically had the lowest rates of inclusion.
- Very few, if any, of the stock assessments provided an indication of the overall value of including environmental knowledge on the advice or management outcomes. Science and management would benefit if stock assessments which included climate change information were evaluated to document what difference the inclusion made to the advice, and the consequences.
- A conceptual risk assessment framework (Climate Change Conditioned Advice: CCCA) is proposed to incorporate climate change-related processes into the provision of science advice, with an initial focus on fisheries stock assessment. This framework proposes that conditioning risk-based advice for climate change will facilitate incorporation of climate-change considerations in comparison with directly including climate change variables in an analytical assessment, as these assessments are often limited by uncertainty in, inter alia, understanding the underlying mechanisms.
- This conceptual framework involves determining appropriate climate change-related variables and their appropriate reference periods, developing climate conditioning factors (CCF's) that are suitable across the range of available data and levels of knowledge and understanding, and is only one approach among several to incorporating climate-change related materials into the provision of science advice.
- The risk-based conceptual framework requires further elaboration and to be applied to select case studies to demonstrate how to develop Climate Change Conditioned Advice (CCCA) across the data-richness and process-knowledge continuum, in particular how to identify appropriate climate, oceanographic and ecological variables, and their appropriate reference or baseline periods.
- Stock exploitation advice would likely be improved (or more robust) if DFO developed an overarching DFO Climate Change Science Strategy, to include climate-change considerations into science advice that informs the delivery of mandated responsibilities.

- More climate-inclusive advice would also require an implementation strategy that would build upon the Climate Change Science Strategy to provide a systematic approach to implementing climate-change considerations into science advice.
- The meeting advises that additions to DFO stock assessment reports are needed to include climate change-related materials, such as information derived from DFO Ecosystem Status reporting processes to provide the contextual background information to understand climate impacts on science advice and stock assessments, and to state whether, what, and how climate change information/processes were considered in that assessment. Data and knowledge gaps preventing the consideration of climate change information/processes in the assessment should also be clearly identified.
- Multi-year to decadal climate and ocean projections at appropriate spatial scales are necessary if CCCA are to be possible. These are currently not available for Canadian waters.

INTRODUCTION

Scientific advice for biological resource management in the Department of Fisheries and Oceans (DFO) generally consists of evaluating the state of a resource, determining the impact of a human activity on that resource state, and comparing the results against some implicit or explicit objectives for resource state in the future. There is also typically an evaluation of risk associated with not achieving the objective, and advice is developed accordingly. This approach has many assumptions, perhaps most importantly for this advice that the environment with which the resource (e.g. a fish stock) interacts is constant or varies without trend. Climate change, however, tends to be a directional and non-random process that potentially alters the mean and possibly higher moments of the state variables (e.g. numbers at age), and could invalidate advice for resource management unless the advice is conditioned to climate change. Climate change affects the achievability of some objectives and can change how a resource, like a fish stock, responds to fishing or other human activity, subsequently influencing a stock's resilience and ability to recover from disturbance.

DFO produces many kinds of science-based fishery advisory documents each year. A common characteristic of each is that the advice is risk-based, such as i) estimating the state of a resource, ii) the probability (or risk) that this state metric is already outside the relevant biological reference condition, and iii) the probability (or risk) that the state of the resource would be outside biological reference conditions under one or more alternative management scenarios. Advice includes outcomes of possible future actions and therefore, implicitly or explicitly, should provide the risk of some state in the future relative to its reference condition. Assessment of risk is also present in other areas of DFO's business, for example in the Fisheries Protection Program (FPP). 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 quantified or made assumptions about the productivity of the habitat in its current state, and how productive the habitat would be after alteration by a particular project. Risk-based advice in the Department is usually provided for at least two different purposes: i) tactical advice, which is developed to inform managers of the relatively short-term impacts of a work, undertaking, action, or fishery (WUAF), or ii) strategic advice, which informs managers of the potential impacts of a WUAF over longer terms than tactical advice.

In reviewing the risks of climate change to programs and sectors of DFO as part of the Aquatic Climate Change Adaptation Services Program (ACCASP), expert assessments concluded there is a high probability of significant impacts on living aquatic resources in all the major aquatic basins of Canada (Arctic, Atlantic, Freshwater, and Pacific) (DFO 2013a,b,c,d). The time frame and the nature of the impacts of climate change vary considerably among regions but the assessments concluded that in general the overall changes are expected to increase with time and will likely become pronounced by mid-century (2050-2060). Although there is evidence of climate-related impacts in all regions, the Arctic basin has already seen the most substantial changes in physical and biological environmental features. From the perspective of vulnerability to climate change, Canada ranked 54th out of 147 countries in a recent review (Blasiak et al., 2017), which makes it more vulnerable than other countries that have, or are developing, methods to include climate change in fisheries advice (USA ranked 142nd, Australia ranked 133rd, European nations ranked between 79th and 147th, and South Africa ranked 130th). Canada's greater vulnerability was determined by the Intergovernmental Panel on Climate Change based on sea surface temperature projections for northerly waters.

As a consequence of these findings and their potential impacts to the resources and their users, the overall objective of this peer review process was to further the development of a scientific framework for incorporating climate change information into fisheries stock assessment advice. This was addressed by considering three sub-objectives:

1. Development of a framework for incorporating environmental variation and climate change into DFO processes for generating stock assessment advice;
2. Reviewing practices and current methods (employed at DFO and internationally) for integrating environmental variation and climate-change considerations into stock assessment advice; and
3. Providing recommendations on best practices for how to include and present environmental variation and climate-change considerations in DFO's stock assessment advice, which is applicable to multiple taxonomic groups and DFO Regions and informative to resources management.

ANALYSIS

Review of current practices for including climate change information into stock assessments

A review (Pepin et al. 2018) was undertaken to evaluate Canadian fish stock assessments conducted by DFO to determine how environmental parameters are currently, or have been recently, applied in models, assessments, or management advice, and to place DFO's work in context with efforts conducted in other national and international fisheries advisory programs. It became clear early in the review process that Climate Change considerations could not be viewed independently of short-term fluctuations in environmental conditions or ecological changes in ecosystem dynamics. Environmental drivers were therefore classified into three categories:

- Climate drivers, which characterize long-term (multi-year) variations and trends in regional or large-scale atmospheric processes or drivers of broad-scale physical properties;

- Oceanographic drivers, which can be strongly associated with climatic variability but also include short-term and/or regional variability in the state of the environment; and
- Ecological drivers, which include a broad range of ecosystem features consisting of trophic interactions, habitat requirements and their interactions.

The review examined 178 DFO stock assessments, dating from 2000-2017, although the majority (~88%) were published after 2009. The authors reviewed published CSAS Research Documents Science Advisory Reports, Science Responses and Proceedings Series as well as stock assessment advice provided for some Pacific salmon (*Oncorhynchus spp*.) stocks in Pacific region which are often provided within Fishery Bulletin notices, Salmon Outlook reports, and Canadian Technical Reports of Fisheries and Aquatic Science. “Recovery Potential Assessments” were excluded. They also examined stock assessments for international and bilateral transboundary stocks for which DFO provides scientific support. For every stock considered, the most recent DFO assessment was included in the review. They included all taxonomic categories (anadromous, groundfish, invertebrates, pelagic, mammals, and elasmobranchs) from all DFO regions.

Four main questions were evaluated for each documented stock assessment. Question 1 considered whether conceptual hypotheses between climate, oceanographic, and/or ecological variables and the stock were identified. Question 2 considered whether climate, oceanographic, and/or ecological variables were included *quantitatively* in the assessment, and how they were included. Question 3 considered whether climate, oceanographic, and/or ecological variables were included *qualitatively* in the assessment, e.g., to interpret status, trends or anomalies in stock indices, such as survey catch per unit effort. Question 4 considered whether the final consensus science advice included climate, oceanographic and/or ecological considerations.

While 46% of the stock assessments described hypotheses or broad-scale conceptual linkages between climate, oceanographic or ecological variables and population dynamics, analytical incorporation of these factors was much lower, with quantitative incorporation in only 21% and qualitative interpretation in only 31% of assessments. In most cases, when climate, oceanographic or ecological variables were quantitatively or qualitatively incorporated into the stock assessment, the resulting advice included statements about the importance of climate, oceanographic or ecological considerations (Fig. 1). Overall, 27% of assessments included climate, oceanographic or ecological information in the provision of advice, principally in terms of how harvest control rules may need to be altered. These rates are considerably greater than the 2% of stock assessments worldwide which included information on climate or environmental drivers in tactical management decisions (Skern--Mauritzen et al. 2016).

The contrast between the conceptual knowledge and the inclusion of climate, oceanographic or ecological information into the advice highlighted that the science-based process typically sets high requirements for the incorporation of environmental knowledge in the advisory process. Uncertainty in understanding the underlying mechanisms was often cited as a limitation for not using environmental information in the provision of advice. Mechanisms were considered important because as the environment and ecosystems change, the complex interactions among climate, oceanographic and ecological variables may shift the relative dominance of one driver over another. Such occurrences are likely to be common and can result in the breakdown of relationships that had previously appeared reliable.

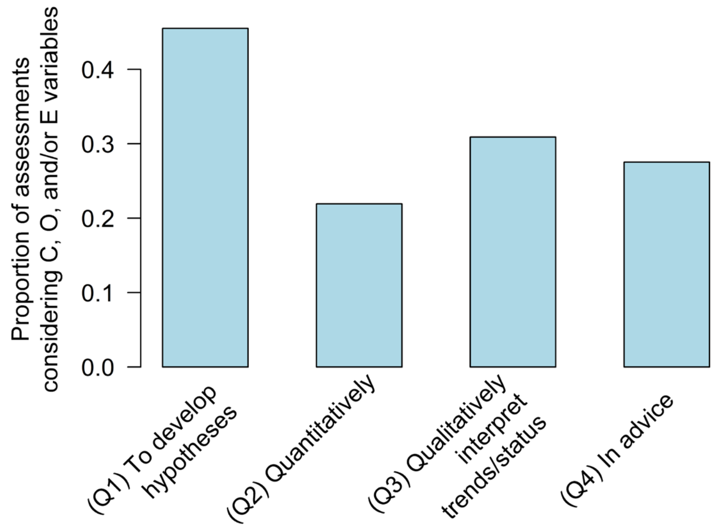

Figure 1. Proportion of assessments that incorporated climate, oceanographic, and/or ecological variables to (Q1) provide conceptual hypotheses of stock responses to potential climate-linked variables, (Q2) quantitatively assess status, (Q3) qualitatively interpret trends or status, and (Q4) provide advice (n=178). Many assessments used multiple approaches.

Across all four questions, stock assessments of anadromous fishes, particularly Pacific salmon, consistently had a higher rate for including climate, oceanographic or ecological variables in the final advice. In contrast, elasmobranchs and marine mammals typically had the lowest rates of inclusion. Salmonid population dynamics tended to be highly coupled with dominant climate and oceanographic features and have frequent assessments owing to their relatively high traditional, recreational and commercial values and few age classes in the spawning population. In contrast, elasmobranchs and marine mammals are generally managed as bycatch or subsistence fisheries, often with multi-annual assessments and relatively simple assessment models. Pelagic, invertebrate and groundfish fisheries represent the bulk of commercial fisheries and included a mixture of highly productive high-value and low value fisheries (Table 1). However, while evaluations of the use of environmental knowledge often considered improvements to model fit, the evaluations seldom determined the impact of the knowledge on accuracy and reliability of advice or management outcomes.

Table 1. Fractions by taxa of total number of DFO stock assessments examined which considered climate, oceanographic, and/or environmental variables related to climate change processes in conceptual, quantitative, qualitative ways and in the resulting assessment advice itself.

Taxa	Concept	Quantitative	Qualitative	Advice	N
Anadromous	**0.58**	**0.65**	**0.46**	**0.58**	26
Pelagic	**0.50**	**0.14**	**0.43**	**0.36**	14
Invertebrate	**0.53**	**0.17**	**0.36**	**0.26**	53
Groundfish	**0.44**	**0.15**	**0.22**	**0.15**	59
Mammal	**0.21**	**0.11**	**0.21**	**0.26**	19
Elasmobranch	**0.14**	**0.00**	**0.14**	**0.00**	7

The development of hypotheses regarding linkages between climate, oceanographic or ecological variables and population dynamics, and the subsequent quantitative or qualitative incorporation of these variables into stock assessments, builds on the degree of understanding of the biology of the target species and surrounding environmental conditions and variability. The level of relevant understanding differs considerably among stocks. Many Atlantic stocks have data that span several decades whereas Arctic stocks typically have data from 10 years or fewer. Differences in the frequency and method of incorporating climate, oceanographic or ecological variables likely reflect differences in the strength of mechanistic understanding of pathways of effect and the level of confidence in statistical relationships. They may also reflect differences in the magnitude and strength of the climate, oceanographic and ecological changes that affected each stock. Further analysis can help determine the reason for differences among stocks and regions but the decision process taken for exclusion of the climate, oceanographic or ecological variables was not always detailed other than to reference uncertainty. Because a driver has not undergone large changes does not imply that the effect is not an important factor affecting a population.

The incorporation of climate, oceanographic or ecological variables into stock assessments showed regional and taxonomic patterns. The assessment of anadromous fish stocks was dominated by Pacific salmon stocks. Relationships between Pacific salmon survival and large-scale climate indices have been well documented (e.g. Hertz et al. 2016). Groundfish assessments more frequently included ecological variables than oceanographic or climate variables, partially because large-scale changes in community composition and ecosystem function have been observed in many of these fisheries, particularly in the Atlantic regions where limited recovery of groundfish stocks following the fishery-environment induced collapse is likely to have been affected strongly by prey-predator interactions. The Central and Arctic Region included climate, oceanographic or ecological variables least frequently among the regions because most of the stocks there are data-limited for which the mechanisms driving population dynamics are poorly understood.

In most assessments that included climate, oceanographic or ecological variables, the variables were used to describe time-varying parameters (quantitative inclusion) or trends (qualitative inclusion) and anomalies in the time-series of the stock population dynamics. Changes in habitat availability and dependencies were also included in responses to all four answers, highlighting recognition of importance of habitat considerations on stock productivity. When climate, oceanographic or ecological variables were not included in the advice or recommendations from an assessment, the most frequent explanations given were data limitation or a lack of understanding of the pathway of effect. However, a large proportion of the stock assessments examined did not report on the degree to which they considered environmental factors when assessing the population state or conducting projections. Many case studies of international stock assessments that were reviewed highlighted linkages to large-scale climate drivers, such as sea surface temperature linked to the North Pacific Index, the El Niño-Southern Oscillation (ENSO) index or the variability in the dynamics of the California Current system (e.g. García-Reyes and Sydeman 2017).

Despite the differences among regions, taxa and assessment types, a clear pattern was apparent. Climate, oceanographic or ecological variables are incorporated into stock assessments in situations where their impact has become most apparent as a result of the strength of the signals. Pacific salmon are highly responsive to the substantial changes in ocean conditions in the region; the productivity of Atlantic groundfish stocks is strongly affected by prey-predator interactions, either in the form of prey availability off Newfoundland (Buren et al. 2014) or changes in mortality associated with predation by marine mammals in the Gulf of St. Lawrence (Swain and Benoit 2015); production of northern shrimp is strongly associated with changes in the timing of the spring phytoplankton bloom and the abundance of predators; and future catches of snow crab are strongly linked to the extent of appropriate thermal habitats during the first year of life. In all instances, changes in the key drivers have often ranged from minima to maxima in the historical records.

Environmental variables may also have been considered explicitly or implicitly in assessments for various stocks but not explicitly included in the recommendations of that assessment, for a variety of reasons. Considerable background research is required to understand the linkages and pathways of effects between climate, oceanographic or ecological variables and stock productivity and status. There are some cases where research is being carried out (e.g. Arctic marine mammal and fish stocks) to develop the necessary understanding to incorporate climate, oceanographic or ecological variables into stock assessments, but the level of investigation varies considerably among stocks.

A limited set of climate, oceanographic and/or ecological metrics have been used in DFO stock assessments to provide science advice (Table 2), but their inclusion was often not rigorously evaluated *a priori* to determine if they described the underlying mechanism affecting the population or whether they provided proxies of correlated processes at large spatial and temporal scales. Climate metrics integrate conditions over large spatial and temporal scales usually indicating long-term trends instead of inter-annual fluctuations. These metrics were more predominant for assessments of anadromous species across all regions, which commonly considered climate metrics which capture dominant oceanographic features (e.g., Pacific Decadal Oscillation and El Niño-Southern Oscillation in the Pacific, Arctic Oscillation Index in the Arctic Ocean, Atlantic Multi-decadal Index in the Atlantic Ocean). Temperature, an oceanographic metric, was the most commonly used across taxonomic groups and regions. Temperature can be measured accurately and precisely relatively easily, is coherent across relatively broad spatial scales, and reflects general features of ocean state. Predation was the most common ecological consideration in both quantitative and qualitative analyses, especially for groundfish, although plankton abundances and species composition were also included in several assessments (especially for pelagic, invertebrate and anadromous species). These ecological metrics are more difficult and/or costly to measure precisely, limiting their availability in many assessments.

Table 2. Climate, oceanographic, and ecological metrics considered in DFO stock assessments.

Climate metrics	Oceanographic metrics	Ecological metrics
Ice extent, depth, dynamics	Temperature (water, air, surface, bottom, etc.)	Abundance of predators (or trends)
Cold Intermediate Layer, CIL	Salinity	Abundance of prey (or trends)
North Atlantic Oscillation	Surface wind stress	Copepod biomass
Atlantic Multi-decadal Oscillation	Near-surface ocean currents	Euphausiid biomass
Arctic Oscillation Index	Current variability	Timing and duration of spring bloom
Northern Hemisphere Sea-Surface Temperature	Pressure-adjusted sea level anomalies	Abundance of competitors (or trends)
Pacific Decadal Oscillation	Ekman transport	Community structure
East Pacific-North Pacific teleconnection Index	Strength of upwelling	Growth rates of another species occupying the same/similar ecological niche
North Pacific Index	Eddy intensity and spatial distribution	
North Pacific Gyre Oscillation	Geomagnetic field intensity and inclination angle	
Aleutian Low Pressure Index	Freshwater levels	
Southern Oscillation Index	Water quality in freshwater	
Strength of El Niño/La Niña (e.g., Oceanic Niño Index)	Precipitation	
	Freshwater run-off and/or river discharge	
	Length of growing season	
	Timing/duration of spring freshet	
	Dissolved oxygen	
	Freshwater habitat characteristics (e.g., gravel, erosion…)	

However, given that simple correlations between proxy environmental indices and population dynamics typically change over time, including climate, oceanographic and/or ecological drivers analytically without a good understanding of ecosystem processes are likely to lose accuracy and precision over time and become increasingly unreliable. This may account for the low proportion of DFO stock assessments which quantitatively included climate, oceanographic or ecological information and provided advice based on these inclusions. It also speaks to the need to carefully monitor departures from empirical relationships to determine when and why they may break down.

The difficulties faced when incorporating climate, oceanographic and ecological variables point to the need to develop a risk-based approach for managing living resources under conditions of climate change and environmental variability.

A strategy to develop climate-informed science advice

A pure process-based approach to considering climate change impacts would incorporate environmental variability and directional change (climate change) directly into fish population models. That is, the environment would just be another variable to help explain variance or inform forecasts of population state. However, there are several concerns with this approach, including: unknown mechanisms driving the interrelationships between abiotic and biotic factors, environmental correlations that disappear over time, misspecification of models, and the overall proportion of risk due to climate change. The alternative is to consider climate change in the advice itself.

Accounting for climate change in advice will involve a process of climate change conditioning of science advice (CCCA), during which appropriate environmental variables reflecting climate change and affecting the dynamics of a resource are identified and linked to the risk assessment component of the advice through assumed or modelled response dynamics.

> 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) and suggests an alteration to the fishery to compensate (or enhance) for this change.

CCCA ultimately requires knowledge or assumptions of the productivity dynamics of a resource and the environmental and ecosystem variables which can influence those dynamics, i.e. there needs to be a causal link between a resource state presently and in the future with one or more variables that are impacted by climate change. Climate conditioning should be considered not as a more complete mechanistic explanation of biological processes which decreases variance due to environmental changes, but as conditioning the advice to account for environmental changes. The latter considers uncertainty in the biological production process and how the inclusion of the climate variable changes the uncertainty which directly relates to probabilities of achieving objectives at acceptable risk levels. This readily translates to risk management, which deals with maintaining acceptable levels of uncertainty associated with management options. This approach is consistent with DFO's precautionary approach (Fig. 2).

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 that no improvement in risk management of human impacts can be achieved by adding the complexity of environmental variability and climate change to the basis for advice. However there is evidence that advice on the impacts of human activities on biological resources can be improved when it is conditioned on environmental conditions and climate change (Tomassi et al. 2017), which justifies making the investigation of possible effects the default assessment approach. Advice conditioned in this way should lead to climate resilient strategies for management of marine and freshwater biological resources. Table 3 provides an overview of DFO core business activities and how climate conditioning is likely to affect scientific advice.

In the annual (periodic) stock assessment processes of DFO (and many other fisheries authorities globally), the formal risk framework for the advice is rarely discussed explicitly. However, the current DFO PA framework (and other comparable frameworks of advisory bodies such as ICES) can be captured fully by these risk-based frameworks. Hence even if the exact terminology below is not commonly used in CSAS Advisory Documents and Departmental discussions, it underlays present practice in most DFO science-based decision-making and climate change becomes just another factor affecting the risk profile in decision-making.

The risk-based nature of DFO science advice can be extended to incorporate climate change effects in a comparable manner to any other factor affecting the management risk profile. This can be done by 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. This approach is based on the concept of **risk equivalency** in resource management advice, which is a means of ensuring that management decisions can be seen as risk equivalent, regardless of the level of data, resource dynamics models or biological production process knowledge of the resource and assessment of its current state. This leads to a consistent application of risk for decision-making. Risk equivalency is achieved through the inclusion of “buffers” which are factored directly into the formulation of advice on managing fishing activities (or other pressures on a resource). The buffers are intended to systematically reduce the recommended level of activity as uncertainty in assessing the relevant risks increases (Punt et al. 2012, Fulton et al. 2016).

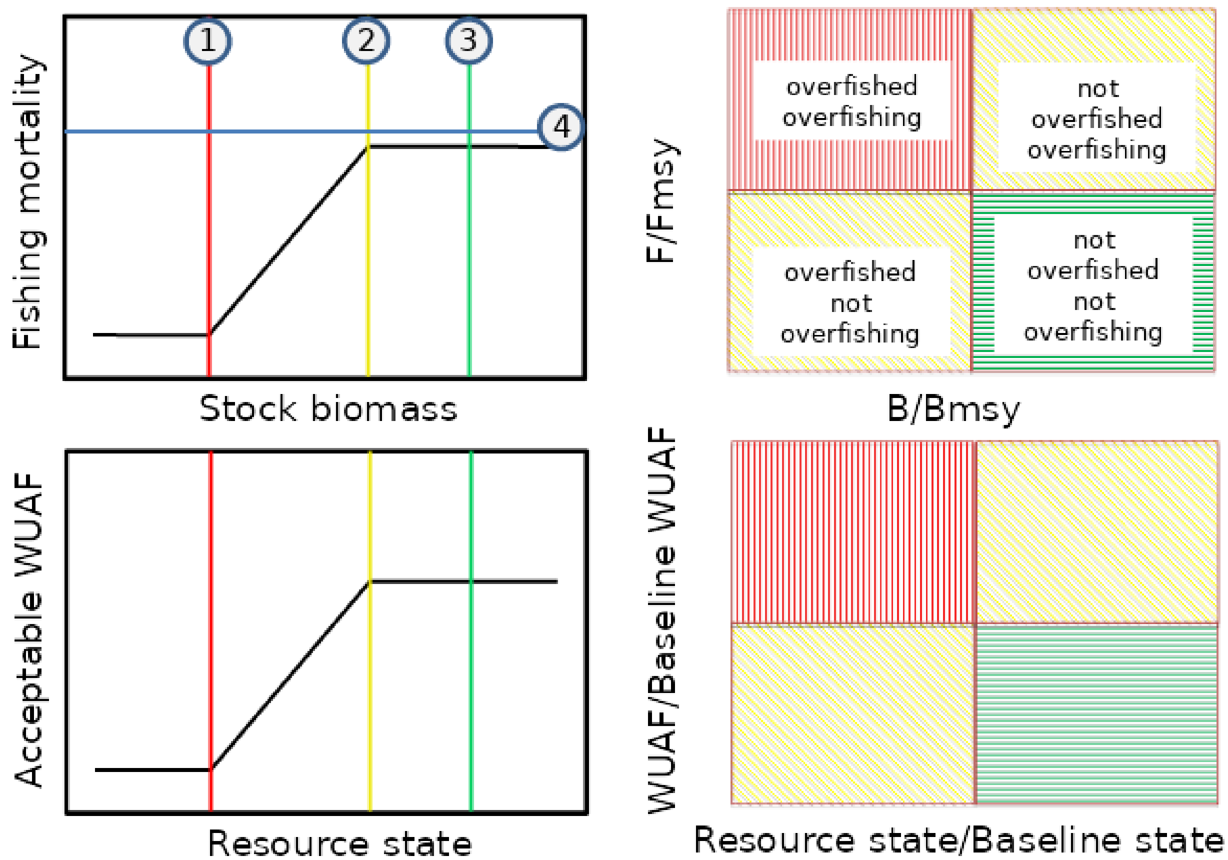

Figure 2. DFO's precautionary approach for sustainable fisheries (top left) generalized to any kind of work undertaking, activity or fishery (WUAF) affecting a biological resource (bottom left). Red (1), yellow (2) and green (3) lines indicate a limit reference point, an upper stock reference point, and a target reference point, respectively, for resource status. The broken stick (reverse Z - black line) represents the rule for managing the WUAF 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 WUAF relative to a chosen reference value ("3" in the upper left panel) which according to UNCLOS and the Fish Stocks Agreement should be the biomass no lower and be the fishing mortality no higher than those giving maximum sustainable yield (Bmsy and Fmsy) in the case of fisheries. The upper left (red, vertical pattern) is then "excessive pressure and resource depleted relative to target", the upper right (yellow diagonal pattern) "excessive pressure, resource not presently depleted"; lower left (yellow diagonal pattern) is "pressure sustainable, resource depleted, and lower right (green horizontal pattern) is "pressure sustainable and resource not depleted".

Environmental state variables (E) are defined as those climate, oceanographic, and/or ecological variables that are potentially affected by climate change and are known or likely to affect the state and dynamics of a resource. The application of the risk equivalency approach then depends on a comparison of the current or projected future set of environmental state variables against the historical, or reference or baseline, environmental conditions (E_{base}) for a resource.

Selecting E variables (e.g. Table 2) will be case-specific and a function of i) the availability and quality of data (including spatial and temporal resolution); ii) the probability and relative rate of change of candidate environmental variables to climate forcing; and iii) potential relationships and interactions between variables. E variables would be resource and/or ecosystem specific, yet may be represented generically as a single measure of environmental state (the E axis, e.g. Plourde et al. 2015) for use in risk evaluation. The definition of E would explicitly consider historical variation, spatial distribution, and reference baseline conditions.

Table 3: Characteristics of broad areas of science-based risk advice activities managed by DFO that affect the state of biological resources, and how climate change conditioning is likely to affect the advice profile. Superscripts: [1] For conditions considered information-moderate or higher for the Department; [2] Upper bound depends on life history of the stock, with only quite long-lived species likely to have advice remain reliable for such longer intervals; [3] Maintain ecosystem structure to support ecosystem function; [4] Recovery of the habitat (i.e. a temporary pressure that will be removed) or recovery of affected populations.

	Time Scale of validity of advice	Predominant kind of advice	Nature of WUAF	Updating	Nature of the thresholds[1]	Possibility that cc conditioning will change the risk profile
Single species stock assessment	1-5 years[2]	tactical	fishing	precautionary approach framework points	explicit, quantitative	possibly
Salmon Enhancement	1-5 years	tactical and strategic (infrastructure)	production schedules, release dates	enhancement target, protection of status quo	explicit for individual programs	likely
Ecosystem approach and multispecies stock assessment	~5 years	strategic	fishing	relative species abundance[3]	implicit or explicit, quantitative	likely
Fisheries Protection Program (with recovery)[4]	1-10 years	mostly tactical into strategic	temporary habitat disturbance	protection of status quo	explicit, quantitative	likely
Fisheries Protection Program	permanent	tactical - strategic	habitat alteration (e.g. filling in)	protection of status quo	explicit, quantitative	very likely
Aquaculture	1-20 years	tactical and strategic	lease siting, fish health	prevention, maximize production efficiency	increasingly explicit	likely
Species at Risk	1 yr to 3 generations	tactical and strategic	fishing, multiple	recovery targets for abundance and time	explicit, quantitative	likely
Oceans (MPA, spatial planning)	periodic, ~10 years	strategic	multiple	enhancement, protection of status quo	Implicit, qualitative. Can be explicit, quantitative for individual species or ecosystem properties	very likely
Aquatic invasive species	until updated	strategic	multiple	prevention	explicit, quantitative	very likely

E_{base} defines the baseline environmental condition(s) upon which current understanding and 'normal' conditions served to derive current limit reference points or harvest control rules for the stocks. Determining the environmental baseline conditions E_{base} is an essential part of applying this risk-based approach to incorporating climate-change considerations into stock assessments. Baseline conditions are defined by the historical frequency, magnitude, and time history of variation in the E variables, and the uncertainty inherent in measuring or modeling E. The introduction of climate-change considerations would aim to capture environmental conditions that deviate from the patterns in E_{base}, including trends and new extremes and reduced or amplified variance in time and space. Duplisea et al. (2018) describe various approaches to determine E_{base} as it relates to resource status and available environmental data. The environmental state for a resource can then be standardized as a deviation ratio from its baseline conditions (E/E_{base}).

The relationship between the probability of a resource being in a given state and the level of a human activity that is being managed is called the **risk profile** (e.g., Fig. 3.). This profile adjusts the response of the resource to human pressure and the available management options to meet an objective, considering uncertainty in resource state evaluation. Environmental conditioning of the risk involves adjusting the risk profile (including uncertainty in resource dynamics) for additional uncertainty that is contributed by environmental deviations from the environmental baseline conditions (i.e., E/E_{base}). Depending on available data, knowledge, assessment methods, sources of uncertainty and the objective and timeframe of the advice, environmentally-conditioned risk profiles can be computed in the assessment model based on one or more functional relationships between one or more components of the resource dynamics and relevant E variables.

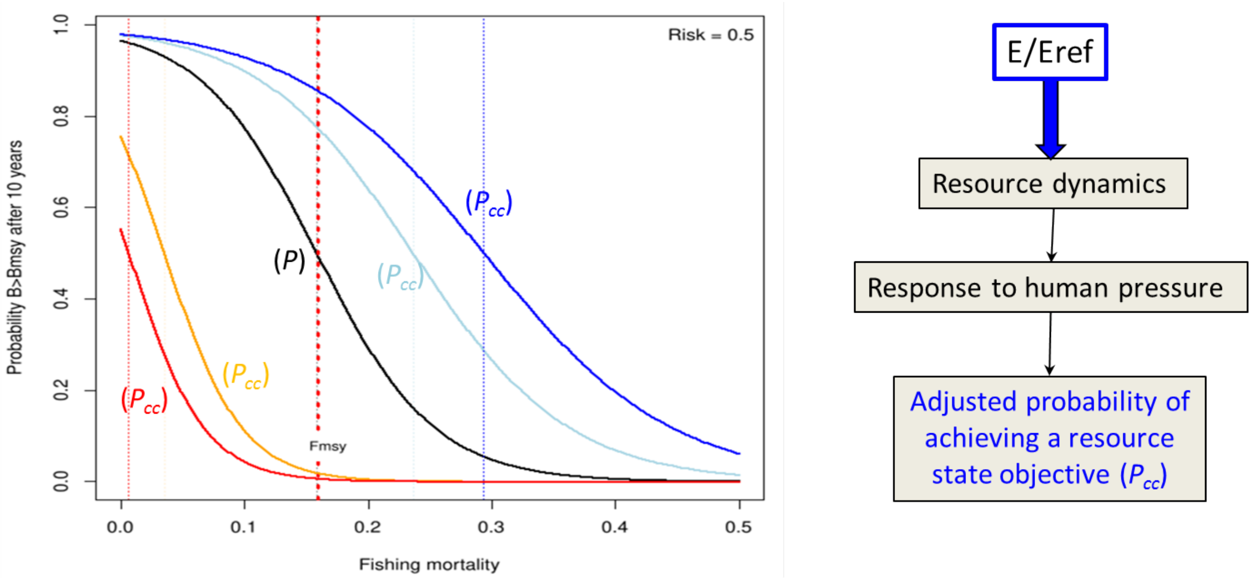

Figure 3. Hypothetical example of climate conditioned risk profiles depicting the probability (P) of achieving a target level (e.g. B > B_{msy} after 10 years (y-axis)) in response to a human pressure (e.g., fishing mortality (x-axis)), under different expectations of some environmental variable E (e.g. sea temperature) and for a set level of risk (e.g., the management risk tolerance (in this case 0.5, top-right corner)). The black line (P) represents the unconditioned advice (i.e. assuming random environmental variation within baseline conditions). The coloured lines (P_{cc}) represent the same advice conditioned for the influence of non-random environmental deviations from baseline conditions. (two warmer scenarios and two colder scenarios). The climate conditioning factor (CCF) would be the ratio of the F with the 50% risk level under one of the climate change scenarios to the F at the baseline scenario.

The change in risk between standard risk profiles in stock assessments and environmentally-conditioned risk profile(s) is termed the **climate conditioning factor**(s) (CCF; Fig. 3). Environmental conditions that may result in a CCF different from zero will require management to adjust the level of human activity to maintain a desired level of risk aversion for a resource (i.e., the management objective). For data-rich cases, climate conditioning factors can be estimated from knowledge of the processes and relationships involved. For data-poor cases, however, climate conditioning factors will need to be determined from some combination of Inference from similar data-rich cases, from other studies of the same species elsewhere or similar species in the area being studied, from life history studies, by scaling-up from laboratory studies, or from expert knowledge.

At present in most cases, it is expected that there has been insufficient exploration (research) to determine the importance of the multiple environmental drivers that may affect population dynamics, and therefore robust relationships of E and resource state will not be available. However, systematically implementing environmental conditioning of the risk will guide knowledge and data acquisition to develop more reliable CCFs and to improve confidence in climate-conditioned science advice. Future work in developing climate change conditioning of science advice (CCCA) should be directed toward developing CCF’s, as this will serve to identify appropriate levels of risk buffering in data-poor and/or process-knowledge limited cases. Illustrative components of DFO fish stock assessments, and how they may be affected by climate change at different time scales, are shown in Table 4.

Table 4. Example of components of standard fisheries assessment advice, and how they are affected by climate change at different time scales.

Factor	Property	Time Scale	Interaction	Requirement to manage risk
State	Spawning Biomass	Annual	Climate change might cause changes in size-at-age 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 to manage the risk of insufficient prey for all predator needs
Pressure	Fishing Mortality	Annual	Over-wintering mortality become more variable as winter ice conditions become less predictable	Making m in annual stock assessments conditional on E/E_{base} (perhaps ice-out timing) so F varies inversely and manages the risk of stock total mortality being unsustainable in unfavourable ice years.
		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 spawning 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
Adjusting P itself		Annual	Protected species taken as bycatch enter the fishery area in 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

Factor	Property	Time Scale	Interaction	Requirement to manage risk
		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

In the variety of stock assessments conducted by DFO, there are likely to be some for which the inclusion of climate change impacts will not be necessary. For example, in providing short-term (tactical) science advice, the dominant uncertainties in stock assessment at this scale usually centre around two components of productivity: recruitment and mortality. The circumstances under which these may be affected by climate change need to be investigated. However, it is important to recognize that **strategic** components of advice may be affected as well and therefore the process of climate change conditioning should still be considered in all cases where climate change effects are plausible. In addition, most biological resources managed by DFO do not have mechanistic models allowing full development of risk profiles. In situations with poor process knowledge and/or data, a buffering approach is considered appropriate and feasible (e.g., Fig. 4).

This approach is a means of applying buffers to “standard” advice which are intended to account for changes in productivity and the risk of not achieving objectives owing to other factors such as data quality or climate change.

The characteristics of climate conditioning factors and climate change conditioned advice are defined in Table 5. A flow chart of the process for developing climate change conditioned advice is illustrated in Fig. 5.

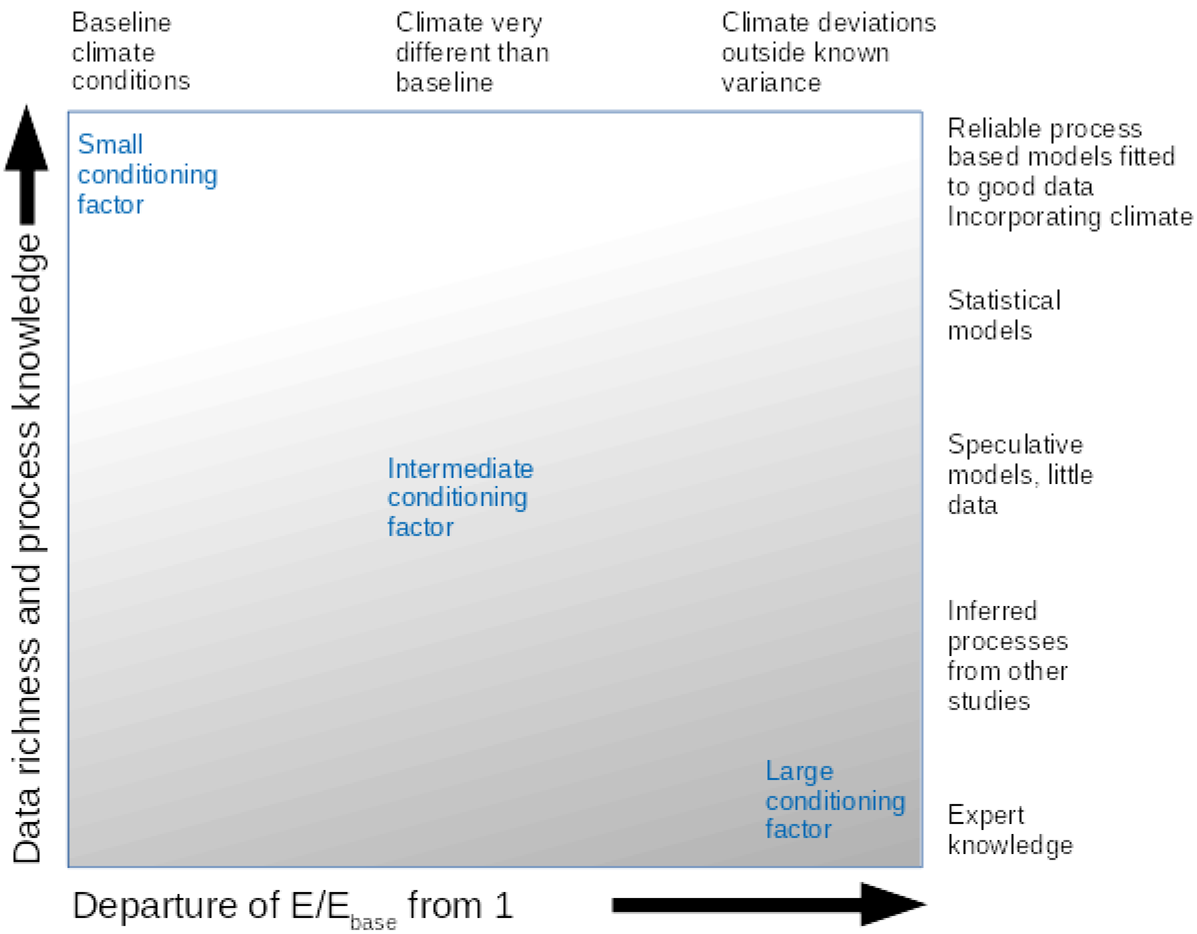

Figure 4. Uncertainty buffer related to level of understanding and deviations in E/E_{base}. No data buffer is applied when impact of E on X is incorporated into state variable estimates/models (internal and highest form of assessment). Buffers are referred to as climate conditioning factors (CCF) in this document and would likely be multiplicative factors on the activity controlled through management such as fish mortality. Generally, with less process information, authorizing a similar level of human activity entails more risk of harm thus a moderating buffer will be larger. However, application of the buffer would not be symmetrical and must recognize that buffers are more likely to be used as penalty on activity rather than an enhancement.

Table 5. Key characteristics of climate conditioning factors (CCF) and climate change conditioned advice (CCCA).

Term	Definition
Climate Conditioning Factor (CCF)	Change in Risk as a result of E departing from E_{base} Key components: - **Magnitude** of E departure from E_{base}

	- Data availability/quality - Level of understanding of human pressure effects on Eres - Level of understanding of E effects on resource dynamics
Climate Change Conditioned Advice (CCCA)	Advice conditioned to achieve risk equivalency under climate change Key components: - **Frequency** of CCF ≠ 0 - **Recurrence** of CCF ≠ 0 - **Purpose and timeframe** of the advice
Environmental variable affected by climate change (E)	An environmental variable or amalgam of environmental variables that are affected by climate change and which in turn impact the productivity of a fish stock. E_{base} is the baseline level of E which could be considered "normal" conditions for the basis of comparison and assessment of E deviations.
Process knowledge	The researchers' knowledge of the biological process and how it is affected by climate change. This includes the ability to develop mechanistic or statistical models of the process which could be used in quantitative analysis.
Risk profile	The change in probability that a human controlled action (fishing) will harm a stock and affect the ability to achieve the stock objective. Described by a curve of probability vs level of fishing for a given objective. A change in the risk profile refers to how that curve can be altered by climate change or another factor. A risk profile altered by climate change is referred to as Pcc

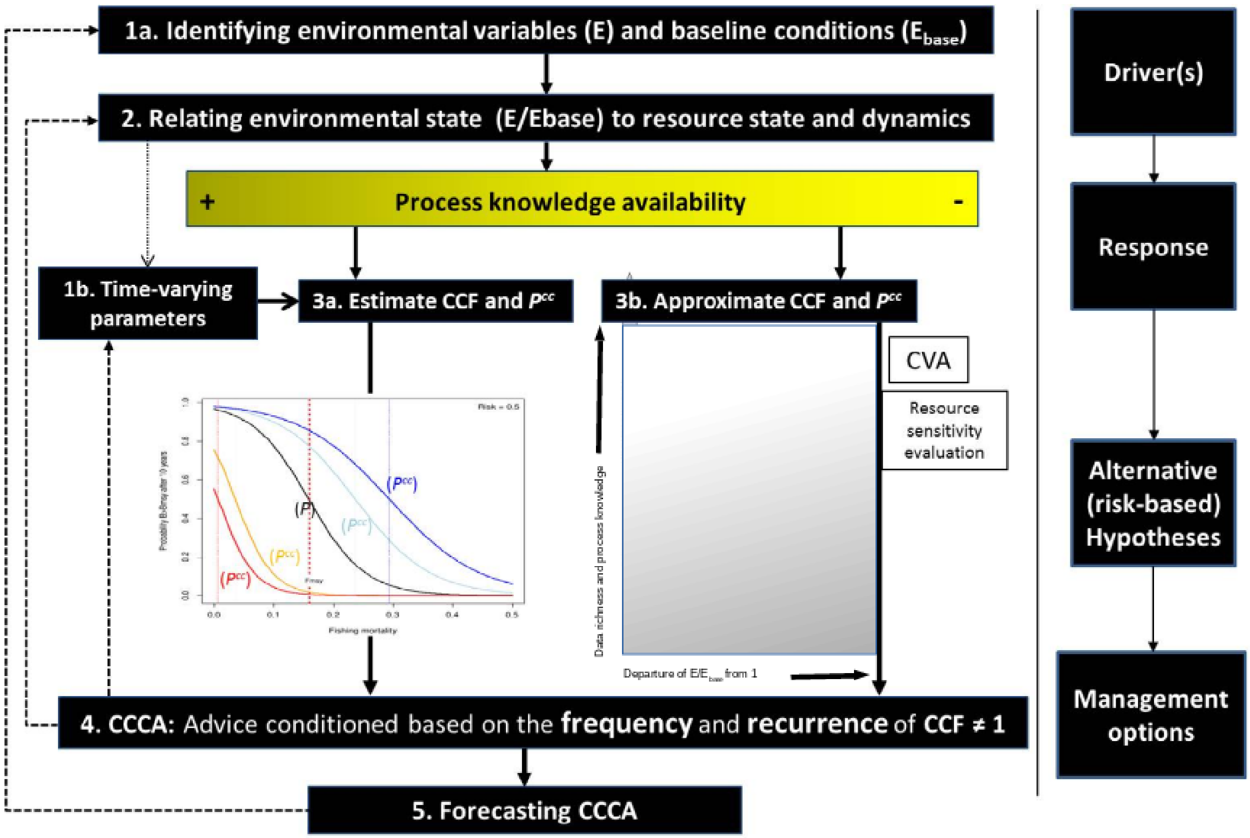

Figure 5. Flow chart illustrating the key components, pathways and processes involved in producing climate change conditioned advice (CCCA). The black (solid) and blue (dashed) arrows represent stepwise and iterative implementation processes, respectively. Depending on knowledge and data availability, response evaluation (step 2) and the formulation and testing of alternative risk-based hypotheses (climate-conditioned risk probabilities P_{cc}) will be performed directly within a quantitative model for resource evaluation (step 3a) or indirectly via the estimation of climate conditioning factors (CCFs) (step 3b). The use of time-varying parameters with underlying climate change hypotheses (step 1b) can serve to explore alternative scenarios in assessment models and estimate P_{cc} until relevant drivers (E) and baseline conditions (E_{base}) are identified (step 1a). Climate change conditioned advice (CCCA) for resource use (step 4) is formulated based on the frequency and recurrence of E departures from E_{base} (corresponding to CCFs different from zero). Future forecasting of CCCA to explore longer-term thresholds and trade-offs is a recommended next step (step 5).

Sources of Uncertainty

Pepin et al. (2018) examined 178 Canadian stock assessment documents produced by DFO over the period 2000-2017, for their inclusion of climate change-related processes. However, the review process noted there are considerably more fish and invertebrate stocks in Canada which are not assessed by DFO. In addition, it is known that some DFO stock assessments have considered climate change-related processes, but found them not to make a difference to the advice, and therefore they were not included or reported on in the assessment documentation for those species. Therefore, the 178 Canadian stock assessments examined, and the resulting numbers which considered climate, oceanographic, and/or ecological processes, are considered to be minimum estimates (meaning that the actual number of stocks which should have climate change-related processes considered, and assessments which did consider climate change-related processes, is likely to be larger than the numbers indicated in this review).

It was also noted in discussion that strategies for incorporating climate change materials into science advice are likely to be similar to strategies for incorporating ecosystem considerations into science advice, because the state of the system and the nature of the interactions in any ecosystem are fundamental elements to implementing a climate science strategy. For example, changes brought about by climate change are likely to be relevant to an ecosystem-based approach. Therefore, addressing climate change factors is one step towards achieving an ecosystem-based approach to providing science advice in DFO. This aspect was not considered in detail in this review process.

CONCLUSIONS AND ADVICE

The work examined in this CSAS process was focused on DFO Canadian stock assessments, but the proposed framework can also be applied to other DFO mandates. Two major (non-exclusive) avenues were recognized going forward to incorporate climate change-related processes into DFO scientific advice. The first, which could be implemented quickly, was to enhance existing stock assessment processes with additional analyses and features that include consideration of climate change-related processes, i.e. to build on current practices. The second avenue is to elaborate and adopt a new framework for including climate change-related processes into providing scientific advice for stock assessment, through the application of climate change conditioned advice (CCCA) and the possible use of climate conditioning factors (CCF's). The following recommendations are proposed to move DFO forward in both of these avenues.

1. It is recommended that DFO develop an overarching DFO Climate Change Science Strategy, to include climate-change considerations into science advice that informs the delivery of mandated responsibilities. Such a strategy needs to be developed with other DFO Sectors (as other major DFO Strategies have been developed) and would:
    a. improve progress on DFO's ability to detect climate change (early warning signs)
    b. provide support for and help to maintain long-term data sets
    c. facilitate broader process-oriented research to understand mechanisms
    d. facilitate climate-informed management decisions
    e. facilitate engagement with other sectors.
2. It is recommended that the Climate Change Science Strategy provide a systematic approach to implementing climate-change considerations into stock assessments and other advisory products and in context with responses to short-term (oceanographic) and ecosystem changes. For stock assessment, such an Implementation Strategy would:
    a. consider Vulnerability/response Assessments as a means, among others, of prioritizing stocks and identifying relevant suites of climate, oceanographic and/or ecological factors to include climate change information into assessments
    b. provide examples of stock assessments for which inclusion of climate change advice may make a difference

c. consider Intergovernmental Panel on Climate Change (IPCC) guidance for attribution and detection of climate change and anthropogenic impacts on stock assessments, to identify mechanisms.

3. It is recommended that the specific information needed for the CCSS Implementation Strategy relative to each major DFO client sector be identified and consolidated into a single document or list of information needed for the Implementation Strategy, and that the present DFO Ecosystem Status reporting process be adapted to address those information needs.
4. It is advised that each stock assessment report includes a description of whether, what, and how climate change information/processes were considered in that assessment, including identification of missing and/or existing knowledge gaps preventing the consideration of climate change information into that assessment. Guidance on how to do this needs to be developed and implemented, taking into account data quality and varying requirements of different stocks and assessments.
5. It is recommended that those stock assessments which included climate change, oceanographic, or ecological information be examined to understand what difference the inclusion made to the advice, and the consequences. The examination should include assessments which explored climate factors in the assessment but such factors were not included in the advice, as comparisons. Results would be used to understand current successful applications and whether their approaches can be applied to other assessments.
6. It is recommended that the risk-based conceptual framework be further elaborated to demonstrate how to develop Climate Conditioning Factors and Climate Change Conditioned Advice across the data-richness and process-knowledge continuum. Establishing a Working Group is one approach to accomplish this goal.
7. It is advised that the risk-based conceptual framework proposed here be elaborated to demonstrate how to identify appropriate climate, oceanographic and/or ecological variables and their reference periods. Experiences and uptake of this conceptual framework should be monitored to understand how and where it works, and that the framework be regularly updated as experience with the framework accumulates.
8. It is concluded that additional science advice is needed to identify climate, oceanographic and/or ecological variables that can be used to incorporate climate information into stock assessment, and their reference periods. A workshop which includes examination of selected case studies to demonstrate various approaches and their utility to both longer-term strategic and shorter-term tactical assessment advice would contribute to this goal.
9. It is advised that multi-year to decadal climate and ocean projections at appropriate spatial scales are necessary for effective inclusion of climate change and environmental drivers in advice for fisheries management, but they are currently not available for Canadian waters.

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SOURCES OF INFORMATION

This Science Advisory Report is from the May 8-9, 2018 meeting titled Framework for Incorporating Climate Change Considerations into Fisheries Stock Assessment. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

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