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Incorporating climate, oceanographic and ecological change considerations into population assessments: A review of Fisheries and Oceans Canada's science advisory process

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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TABLE OF CONTENTS

ABSTRACT

We report on the use of climate, oceanographic and/or ecological considerations in Fisheries and Oceans Canada's stock assessment science advisory process. Our evaluation is based on the most recent population assessment for 178 stocks in which Canadian government scientists play a leading role. Assessments were conducted principally through the peer-review process managed by the Canadian Science Advisory Secretariat but other sources include regional peer-reviewed technical evaluations as well as transboundary stocks. We evaluated whether climate, oceanographic and/or ecological information was considered in terms of hypotheses or broad-scale considerations, through quantitative or qualitative analyses, and whether the information served to inform the recommendations concerning current or future stock status. Hypotheses or broad-scale considerations appeared in 46% of assessments; quantitative inclusions occurred in 21% of assessments while qualitative interpretations appeared in 31% of assessments; and 27% of assessments included climate, oceanographic and/or ecological considerations in the advice. Assessments of salmonids, invertebrates and pelagic taxa were more likely to make use of climate, oceanographic and/or ecological data than groundfish and elasmobranchs. The influence of oceanographic factors and/or ecological interactions were considered more often than the effects of climate variables, although the latter were of particular importance in the Pacific and Arctic regions. An assessment of case studies from other jurisdictions reveals that the application of environmental knowledge in stock assessments is often based on strong initiatives dealing with fundamental research into ecosystem dynamics. Although DFO's stock assessment process appears to make greater use of environmental knowledge than most other jurisdictions, most assessments` do not consider environment factors. Our findings highlight a gap in our ability to respond to climate change based on science advice provided in stock assessments. We provide several recommendations to address DFO's challenges in achieving a nationally coherent, ecosystem-based responsible approach to managing for changes in climate, oceanographic and/or ecological conditions in Canada's three Oceans.

INTRODUCTION

In reviewing the risks of climate change (CC) to programs and sectors of Fisheries and Oceans Canada (DFO) as part of the Aquatic Climate Change Adaptation Services Program (ACCASP), expert assessments (DFO 2013a,b,c,d) concluded that there is a high probability of significant impacts on living aquatic resources in all the major aquatic basins (Arctic, Freshwater, Atlantic, Pacific). The time frame and the nature of the impacts of climate change vary considerably among regions but 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 and the impacts on living aquatic resources are well documented (DFO 2013a,b,c,d).

Impacts of climate change first appear in the physical features of the environment and include (but are not limited to); thermal regimes, shifts in seasonal cycles, changes in the freshwater cycle and conditions, changes in weather patterns and wind forcing that can affect hydrological cycles and circulation patterns, increases in CO_2 and declines in O_2 concentrations, and alterations in habitat availability. There are cascading effects on physiological processes (e.g., growth, behaviour, mortality), life-history features from lower trophic levels to top predators, populations, food web interactions, species composition at all trophic levels and ecosystems (Poloczanska et al 2013; Gattuso et al. 2015). Response to climate change impacts were identified across trophic levels as part of the ACCASP risk assessment (Shackell et al. 2013; Shackell et al. 2014; Stortini et al. 2015; Hunter and Wade 2015) but the nature of those impacts will likely vary considerably among taxa, with some taxa benefitting (e.g., through range expansions, improved physiological performance), while others may experience harsher environmental conditions (e.g. thermal lethal limit, competition from new/invading taxa, changes in habitat availability, changes in prey fields etc.). DFO’s risk assessment reviews highlighted important differences in the nature of environmental changes projected in the different bioregions (DFO 2013a,b;c,d), yet together emphasized the importance of identifying common approaches to assess the consequences of climate change on living aquatic resources (Shackell et al. 2014; Hunter and Wade 2015).

It is essential to consider the nature of climate change relative to the underlying natural variability in systems when evaluating the potential impacts on aquatic organisms. Climate change will result principally in a directional change in baseline conditions, which in some parts of Canada’s aquatic environments may be considerably smaller than the underlying variability in oceanographic variables (e.g. temperature, salinity). However, these changes may nevertheless cause environmental conditions to regularly exceed maxima/minima previously encountered within each region (e.g. acidification, ice formation and retreat, summer temperature). In addition to altering extremes, climate change will likely result in substantial changes in seasonal environmental cycles (e.g. seasonal warming/cooling, hydrological sources and flows) that can have important differential impacts among taxa within an ecosystem because not all species may be able to adjust the timing of life history events to match altered seasonal conditions, and there may be increases in the likelihood and severity of extreme events (Herring et al. 2018). Because of the complexity of alterations in the physical environment resulting from climate change, developing accurate predictions of their consequences for ecosystem or population productivity was not possible during DFO’s most recent risk assessments (DFO 2013a,b,c,d). Gaps in knowledge, particularly the underlying functional responses of organisms to changes in environmental conditions (physical and biogeochemical) as well as understanding of the causes of historical trends, were the principal limitations in the development of detailed quantitative forecasts (DFO 2013a,b,c,d). Nevertheless, there was a high degree of confidence in the qualitative assessments of expected impacts of climate change across most trophic levels largely as a result of integration of knowledge from the scientific literature.

Most peer-review processes overseen by the Canadian Science Advisory Secretariat (CSAS) aim to provide recommendations to decisions makers about the consequences of management actions, and an evaluation of the uncertainty regarding forecasts of future states based on knowledge of the past and the consequences of human activities (e.g. harvests). The primary products of DFO's advisory processes are: [1] single species population assessments, including species-at-risk; [2] fishery production potential evaluation of the impact of human activities; and [3] ecosystem status reports. Duplisea et al. (2018) provide a comprehensive review of the various aspects of DFO's advisory processes and how climate change factors into their objectives. Forecasting the future status, evaluating the capacity of a population to recover from perturbations, and assessing the risk of passing beyond critical thresholds are three common elements of the advisory processes, which have different data requirements. Climate change and environmental variability can act differentially on each advisory target, as well as the ecosystem components with which they interact. Our ability to detect or assess impacts of climate change depends on the strength of these drivers relative to that of other factors. Population forecasts aim to assist managers in planning and decision-making. Sustainable development should be based on environmental, ecological, economic, social, food production and management considerations (Gaichas et al., 2017) that effectively integrate long-term and short-term concerns (Senate Environment and Communications Reference Committee, 2017). However, governance and trade decisions may also have important consequences in determining the effects of climate change on populations (Mullon et al., 2016).

DFO's ability to provide advice depends on the availability of information from a broad range of sources including oceanographic data, fishery independent surveys, catch data, fishing effort, demographic data, age-length-weight-growth data, movement (e.g., emigration/immigration, connectivity), mortality rates, and knowledge or understanding of the relationship between the dynamics of the target taxa and interacting features of the ecosystem (e.g. trophic dynamics, changes in exploitation patterns and pressures). Data availability and quality differs greatly among taxa, stocks and regions, which results in the application of a broad variety of approaches, with different degrees of accuracy and uncertainty in their evaluations of population states. They also differ in their use of environmental variables to explain past and anticipated changes in the stock dynamics. Now that Canada has stated that it has adopted an ecosystem (in contrast to a single species) approach to fisheries management, the challenges are considerable . Within this approach, scientists working on stock assessments now must consider numerous overlapping policy issues, translate broad goals into measurable objectives, and then make the necessary calculations that would suggest acceptable harvest strategies within an ecological framework.

Single species stock assessments represent one of the primary activities of DFO scientists and are based on both quantitative and qualitative approaches. Fundamentally, the goal of stock assessments is to evaluate the state of a population and assess the sustainability of different harvest strategies (impact) based on past observations, project the likely patterns of change on relatively short time scales (1-5 years), and quantify the uncertainty and risks associated with such changes. The basic principles are that future harvest strategies should leave enough fish in the population, after accounting for losses to the fishery and natural ecosystem processes, to maintain a healthy level of productivity for the stock. For many stocks, important benchmarks serve to identify a biomass (or population abundance) level below which productivity may be impacted, or a maximum fishery allowable mortality. DFO's ability to undertake stock assessments is reliant on the availability and quality of data, resulting in the use of many different methods for the provision of advice. In the case of data rich stocks, detailed population models (e.g. state-space, virtual population analysis, etc.) can serve to estimate changes in age/size distribution, evaluate changes in mortality rates and their causes, estimate the impact of harvesting, and project short-term expectations of population state. Assessments of intermediate complexity occur in instances where data availability provide independent estimates of population states and trends and the level of detailed biological knowledge could permit development of partial or advanced population models but knowledge, capacity or quality issues preclude the application of such methods. At the lower end, data poor stocks have very limited sources of information, which makes it challenging to gain a sense of changes in productivity, project future states or evaluate the potential impacts of harvest scenarios.

The direct impact of fishing, as an important source of mortality through the removal of individuals from a stock, is generally viewed as the dominant anthropogenic driver, although secondary effects of genetic or phenotypic selection may alter a population's production potential over the long-term (Edeline et al. 2007, Andersen & Brander 2009, Garcia et al. 2012, Laugen et al. 2014). The ability of scientists to incorporate climate change or environmental information into the advisory process relies on the fundamental research carried out by DFO scientists as well as researchers from other institutions or countries. For environmental information to be effectively included into an advisory process, a degree of confidence is required in our knowledge of how the environmental drivers affect changes in the state of one or several features of the taxa's biology, and the mechanism(s) involved (Edwards et al. 2017). Environmental conditions can act directly on life history parameters (e.g. growth, condition, mortality, maturation, energy allocation, etc.), affect the ability to quantify abundance through any metric (e.g. catchability, timing of migration, etc.), and the time scales over which the effect takes places (e.g. pre-recruit survival events/conditions, growing season, multi-year). Environmental drivers, for the purposes of this review, can be classified into three broad categories;

1. Climate (C) drivers, which characterize long-term (multi-year) variations and trends in regional or large-scale atmospheric processes or drivers of broad-scale physical properties that are often associated with important changes in ecosystem characteristics (e.g. primary production, community structure, distributional shifts);
2. Oceanographic (O) drivers which can be strongly associated with climatic variability, as a result of the commonalities in physical attributes that change over time, but which also often includes elements of short-term and/or regional variability in the state of the environment. These variables can reflect the cumulative effects of changes in weather patterns or departures from the average seasonal cycle that can have impacts on a stock directly or via cascading effects through the food web;
3. Ecological (E) drivers, which can include a broad range of ecosystem features, consist of trophic interactions, and habitat requirements or associations for the purpose of this review. Ecological drivers often demonstrate time-series features that are similar to oceanographic variables in that fluctuations follow periodic patterns of change but in which there can be substantial or abrupt short-term changes that may result from perturbations to one or several ecosystem components.

Ecosystem shifts are often linked to change in ocean state, whether as a result of long- or short-term changes in physical and/or biogeochemical properties. Because the linkage between climate change and variability to fish population dynamics is mediated through the oceanographic and/or ecological drivers, any evaluation of the incorporation of climate information in single species stock assessments could not be carried out effectively without also considering all three categories of Climate, Oceanographic and Ecological variables.

Many empirically-derived relationships between environmental conditions and the response of organisms or populations can place limitations on our ability to predict or extrapolate beyond the range of known conditions because measurement error is an important source of uncertainty and there are often several confounding (correlated) environmental features that can be contributing to the analytical results. Furthermore, many forecasts of population state that were based on environmental conditions have proven to be inaccurate (Myers 1998, King et al. 2015, Hilborn 2016, Szuwalski & Hollowed 2016, Essington et al. 2017) because the underlying assumption of ecosystem stationarity breaks down when there are changes in key trophic interactions or alterations in the relative importance of other components of the system. As a result of uncertainty or a lack of understanding of important drivers of change in aquatic ecosystems, or because the relative strength of environmental change is less than that of other factors (e.g. harvest rates), methods to incorporate environmental knowledge into population assessments are likely to differ greatly among taxa, stocks, regions or peer-review processes but the extent of these differences is currently unknown. To date there is limited knowledge of DFO's efforts to provide an integrated assessment of the use of environmental knowledge into our understanding of changes in the abundance of aquatic living resources. As a result, the aim of this review is to provide an evaluation of Canadian fish stock assessments conducted by DFO to determine the state of application of environmental parameters in models, assessments, or management advice, and place DFO's work in context with efforts conducted in other advisory programs. We aim to describe the points in the assessment processes at which information is applied and how a climate perspective has been used to frame tactical and strategic recommendations. The overall purpose is to present advice to resource managers on the diversity of approaches by which climate change effects have been incorporated into assessments and an ensemble of metrics that can be used in stock assessments to strengthen the advisory process.

The CSAS Science advisory process is conducted principally by DFO scientists with input from external experts (e.g. academic, non-governmental organizations (NGOs), and industry) with a primary focus on quantitative or qualitative analyses of relevant physical, biological and ecological data. Although there may be participation from stakeholders in the scientific assessments and in defining the framework assessment, socio-economic considerations and other factors that are considered (or not) in the final decision-making process concerning exploitation rates or allocations are not currently included in the CSAS review process and were not evaluated in this review.

METHODS: INVENTORY OF CLIMATE, OCEANOGRAPHIC, AND ECOLOGICAL INFORMATION USED IN FISHERIES STOCK ASSESSMENTS

CANADIAN ASSESSMENT

The goal of our review was to determine how climate, oceanographic and/or ecological information was included in the Canadian fisheries stock assessments conducted by DFO. DFO regions responsible for stock assessment advice are Newfoundland and Labrador (NL), Quebec (Q), Gulf (G), Maritimes (M), Central and Arctic (CA) and Pacific (P). In addition to stock assessments produced by DFO, we examined stock assessments for international and bilateral transboundary stocks for which DFO provides scientific support. We reviewed published CSAS Research Documents, Science Advisory Reports, Science Responses and Proceedings Series. Exceptions to this were for 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 Sciences. For Pacific salmon, the review was not comprehensive since numerous assessments exist that are not highly circulated and not publicly accessible. In conducting this review, we recognize that although it is not fully comprehensive (there are harvested species/stocks that are only assessed infrequently, or not assessed at all), it does capture that vast majority of species for which DFO Science advice is provided.

For each stock assessment, we used the most recently published document upon which current advice, or framework for provision of advice, was based. As such, publication dates ranged from 2000-2017 although the majority of documents were published after 2009 (~88%). The stock assessments included in our evaluation are listed in Appendix A.

DFO is also responsible for "Recovery Potential Assessments" (RPA) of species identified as "Threatened" or "Endangered" by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). RPAs follow standard protocols (e.g. Revised Protocol for Conducting Recovery Potential Assessments) to provide scientific advice to a larger process guided by the Species at Risk Act (SARA). Given differences with fishery-oriented assessment processes, RPAs were excluded from the present exercise. However, the results of this review could be used to develop climate change/ecological protocols for consideration in the RPA process.

Four main questions were evaluated in the review of each documented stock assessment (Figure 1). Question 1 addressed whether, and where within the stock assessment document, conceptual hypotheses between climate, oceanographic, and/or ecological variables and the stock were identified. Question 2 addressed whether climate, oceanographic, and/or ecological variables were included *quantitatively* in the assessment, and how they were included. We considered stock assessments that included time-varying biological parameters, such as natural mortality or growth, as examples that quantitatively included climate, oceanographic, and/or ecological variables when rationale was provided linking it to a relevant variable or process. For example, the rationale for including time-varying natural mortality could be due to varying predation rates (i.e. ecological considerations). Question 3 addressed whether climate, oceanographic, and/or ecological variables were included *qualitatively* in the assessment, typically by considering those variables to interpret status, trends or anomalies in stock indices, such as survey catch per unit effort (CPUE). Question 4 addressed whether the final recommended science advice included climate, oceanographic and/or ecological considerations. Many assessments may have discussed or considered, either quantitatively or qualitatively, climate or oceanographic and/or ecological variables but the final recommended advice may not have utilized any of those analyses. In the case where no climate, oceanographic or ecological information was included in the advice the reasons were evaluated, and categorized (e.g. not a concern, unknown mechanism, data limitations etc.) to identify impediments to inclusion. For each question, we documented whether climate, oceanographic or ecological indices or a combination thereof were included, and identified the associated variables (Figure 1). We summarized the review results for emergent themes consolidating material where appropriate.

We did not evaluate the accuracy, rigour or efficacy of inclusion of these variables in projections or forecasts, which was beyond the scope of this initial review. However, this topic is explored further in the discussion.

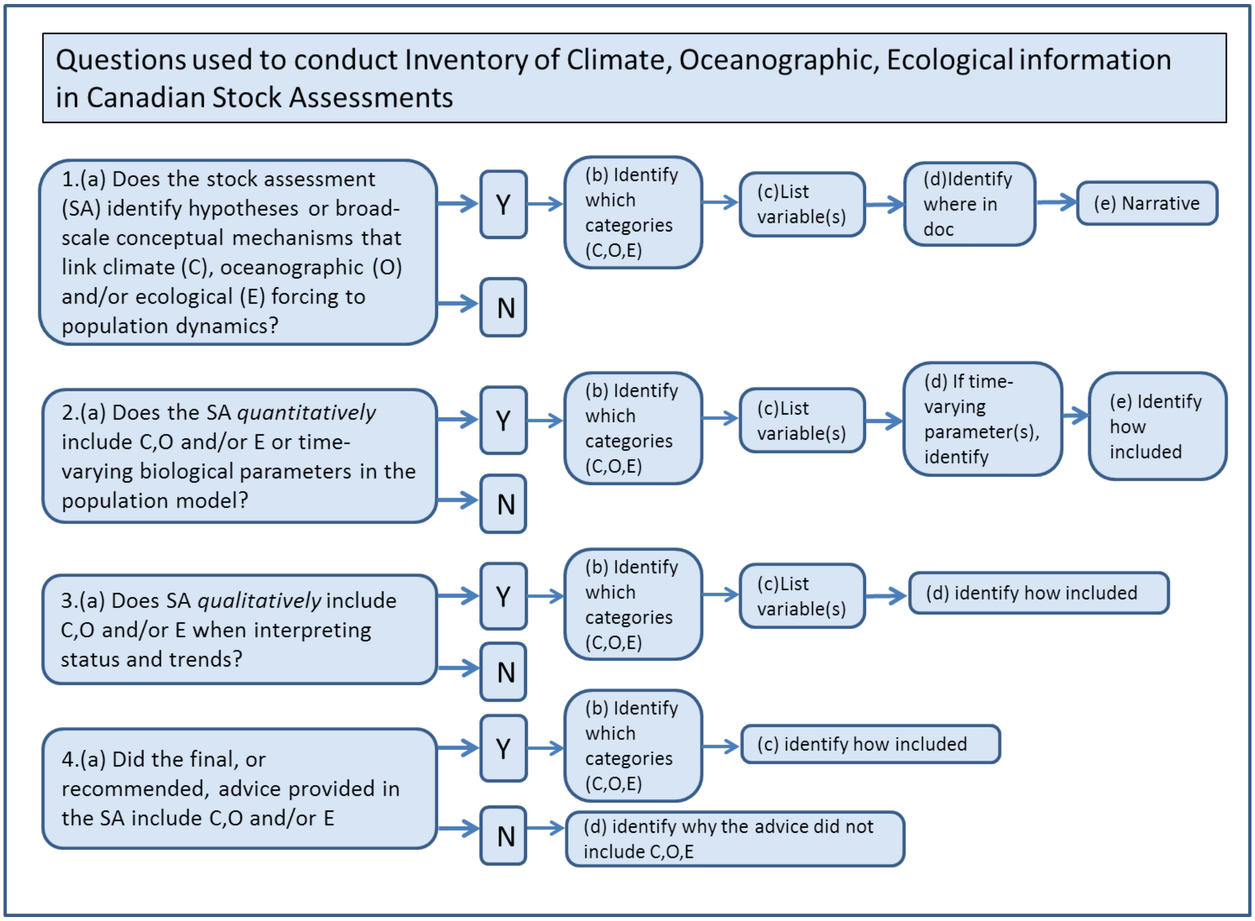

Figure 1. Flowchart used to review the use of climate (C), oceanographic (O), and ecological (E) variables or considerations in DFO fisheries stock assessments.

Climate variables included large-scale forcing, including short-term processes, such as the El Niño Southern Oscillation (ENSO), and long-term processes, such as North Atlantic Oscillation (NAO), Atlantic Multi-decadal Oscillation (AMO) and Pacific Decadal Oscillation (PDO). Sea ice indices were included as a climate variable because of its large-scale, long-term decline in extent and duration due to atmospheric warming. Oceanographic variables were physical drivers and included upwelling indices; sea surface, bottom and river temperature; salinity, freshwater river discharge, dissolved oxygen content and ocean acidification metrics (e.g. pH, carbonate parameters). Ecological variables included predator and/or prey indices and thermal habitat estimates. Climate, oceanographic indices or ecological indices as a group are periodically referred to as “environmental” throughout the text.

GLOBAL PERSPECTIVE

To provide a context for Canadian assessments against other international advisory efforts, we applied the same four question criteria to a series of stock assessments from the United States of America (USA), Australia, Europe (through the International Council for the Exploration of the Seas), South Africa and international Regional Fisheries Management Organizations (e.g. International Commission for the Conservation of Atlantic Tunas). This review was not intended to be exhaustive, but rather aimed to provide examples of some international case studies where climate, oceanographic and ecological variables have been quantitatively and qualitatively used in advice, primarily focusing on examples of climate change. Finally, we also reviewed national or regional strategies for incorporating considerations of climate change into fisheries management where available.

RESULTS – CANADIAN ASSESSMENTS

OVERVIEW

A total of 178 DFO stock assessments were considered in this review. The number and taxonomic diversity of stocks differed greatly among DFO regions (Table 1). There were 27 assessments in 2017 considered in this review, with the number of documents declining as we go back further in time (Figure 2). The occurrence of climate, oceanographic and ecological variables in the assessment documents for which current advice was based on, varied over time reflecting the fact that for most species, the most recent assessment occurred within the last 5 years (Figure 2). Qualitative and quantitative considerations in the climate, oceanographic and ecological variables became more prominent for species with the current assessments after about 2011. Our protocol for review of stock assessments did not provide an evaluation of the historical patterns of climate, oceanographic and ecological variables within each assessment.

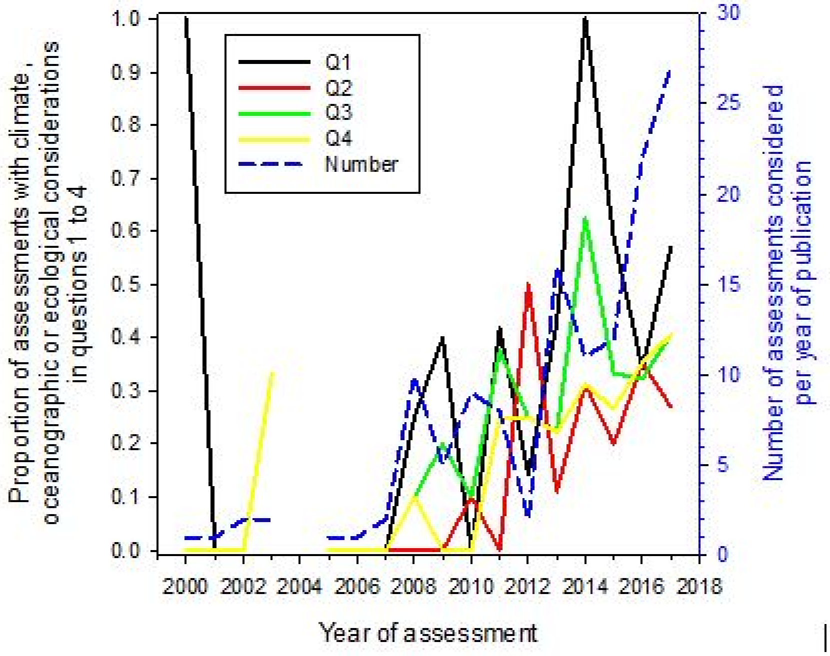

Figure 2. Year-dependent proportion of stock assessments that incorporated climate, oceanographic, and/or ecological variables to highlight broad-scale processes or conceptual hypotheses (Q1 – black line), quantitatively assess status (Q2 – red line), qualitatively interpret trends or status (Q3 – green line), and provide advice (Q4 – yellow line). The number of assessments considered per year is represented by the blue dashed line (n=178) and referenced to the right-hand y-axis.

Of the 178 assessments reviewed in this evaluation, 46% identified hypotheses or broad-scale conceptual mechanisms that link climate, oceanographic or ecological forcing to population dynamics (Figure 3). However, only 21% of the assessments included climate, oceanographic, or ecological variables quantitatively in the population model or time-varying biological parameters thought to be related to climate, oceanographic or ecological variables. Thirty-one percent (31%) of assessments qualitatively included climate or oceanographic variables, or ecological variables when interpreting status and trends. Twelve percent (12%) of assessments included both quantitative and qualitative elements related to climate, oceanographic or ecological variables. Advice and/or recommendations that included the importance or effects of climatic, oceanographic or ecological considerations appeared in 27% (48/178) of stock assessments.

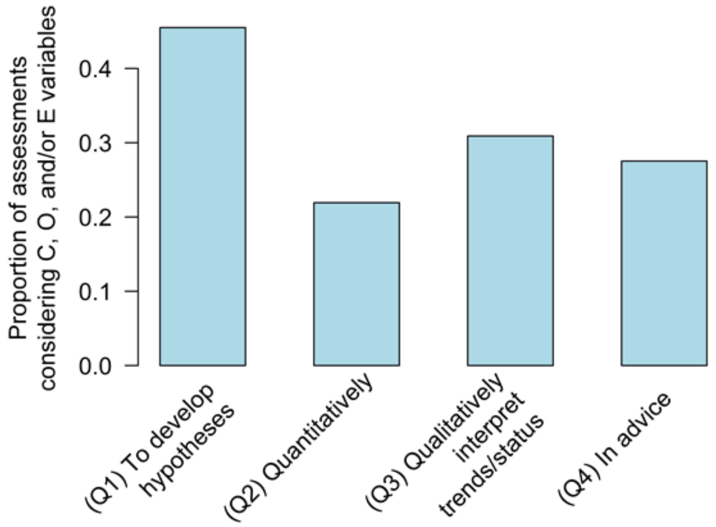

Figure 3. Proportion of assessments that incorporated climate (C), oceanographic (O), and/or ecological (E) variables to provide conceptual hypotheses (Q1 of literature review), quantitatively assess status (Q2), qualitatively interpret trends or status (Q3), and provide advice (Q4) (n=178). Many assessments used multiple approaches.

Table 1. Number of stock assessments by region and taxonomic category considered in this review. DFO regions are Newfoundland and Labrador (NL), Quebec (Q), Gulf (G), Maritimes (M), Central and Arctic (CA) and Pacific (P). Transboundary stocks for which DFO provides advice were also included.

Region(s)	Anadromous	Groundfish	Invertebrates	Pelagic	Mammals	Elasmobranchs	Total
CA	8		2	11	-	-	21
G	1	5	5	2	-	-	13
M	-	7	14	-	2	2	25
NL	1	15	7	-	2	2	27
NL, M, G, Q	1	1	-	-	-	-	2
NL, M, G, Q, CA	-	3	-	-	-	-	3
NL, Q	-	1	-	-	-	-	1
P	15	15	12	3	2	3	50
Q	-	5	13	3	4	-	25
Transboundary	-	7	-	2	2	-	11

Q1 – CONCEPTUAL HYPOTHESES

1. (a) Does the stock assessment identify hypotheses or broad-scale conceptual mechanisms that link climate, oceanographic or ecological forcing to population dynamics?

1. (b) if (a) is yes, identify if climate (C), oceanographic indices (O) or ecological indices (E) are used, or a combination.

1. (c) If response to (a) is yes, identify climate, oceanographic and ecological variable(s) considered.

1. (d) If response to (a) is yes, where are these hypotheses described in the assessment? These hypotheses or mechanisms need not be tested within the stock assessment, but may simply provide a background linking the species' biology or ecology to climate or oceanographic conditions. This is where ecological drivers (e.g. altered prey fields) might be identified.

1. (e) Narrative

We found that 46% (81/178) of recent stock assessments identified hypotheses or broad-scale conceptual mechanisms that link climate, oceanographic or ecological forcing to population dynamics. Oceanographic variables were considered in 74% (60/81) of stock assessments with positive responses to question 1a, either on their own (31/81), with ecological variables (17/81), with climate variables (7/81) or as a joint consideration of oceanographic, climate and ecological variables (5/81). Ecological variables were considered in 46% (37/81) of stock assessments, on their own (15/81), with oceanographic variables (17/81) or with both climate and oceanographic variables (5/81). Climate variables were considered in 22% (18/81) of stock assessments, on their own (6/81), with oceanographic variables (7/81) or with both oceanographic and ecological variables (5/81).

Stock assessments for salmon and other anadromous fishes considered climate, oceanographic and ecological variables most frequently, with 58% (15/26) of anadromous stock assessments including some consideration (Figure 4a). The proportion of stock assessments considering climate, oceanographic and ecological variables was lower in invertebrates (53%, 28/53), pelagic stocks (50%, 7/14) and groundfish stocks (44%, 26/59), followed by marine mammals (21%, 4/19) and elasmobranchs (14%, 1/7).

Among the regions, Gulf more frequently considered climate, oceanographic and ecological variables in broad-scale hypotheses or conceptual mechanisms in the stock assessments (61%, 11/18), followed by Newfoundland (61%, 20/33), Maritimes (60%, 18/30), Quebec (53%, 16/30), Central and Arctic (46%, 11/24) and Pacific (32%, 16/50) (Figure 4b). Multi-region (zonal) stock assessments were the most likely to considered climate, oceanographic and ecological variables (83%, 5/6). However, only thirty-six percent (36%, 4/11) of transboundary stocks included considered broad-scale hypotheses or conceptual mechanisms in their assessments.

Among oceanographic variables, water temperature was most frequently considered (55/81) (Figure 5). Among climate variables, large-scale forcing and cycles (e.g. AMO, NAO, PDO, long-term changes in sea ice; 31/81) were considered more frequently than short-term forcing (e.g. ENSO) (4/81). Among ecological variables, trophic interactions were the dominant consideration (28/81), but habitat changes were also included (4/81).

Hypotheses or broad-scale conceptual mechanisms that link climate, oceanographic or ecological forcing to population dynamics, were most often considered in the background section of stock assessments (39/81) and less frequently in environmental considerations or outlook sections (25/81). Some stock assessments included conceptual issues in the methods (6/81), results (11/81), discussion (5/81) and uncertainty (7/81) sections of the advisory documents. Seven assessments included hypotheses or broad-scale conceptual mechanisms in two or more sections of the document.

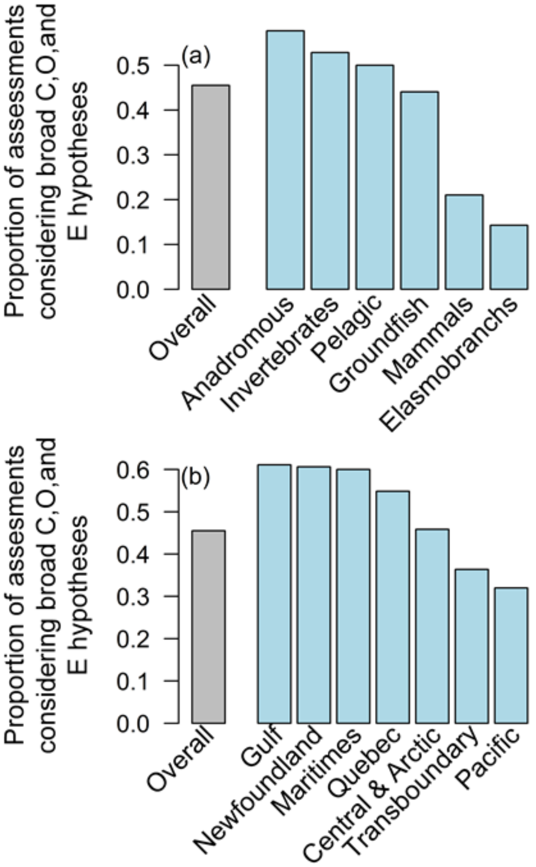

Figure 4. Overall proportion overall of stock assessments considering climate forcing (C), oceanographic (O), and/or ecological (E) variables when developing broad-scale hypotheses or conceptual mechanisms is shown in grey bars (81/178). Blue bars indicate the proportion by (a) taxonomic groups and (b) regions. Several assessments included multiple regions, and were therefore were included multiple times in (b).

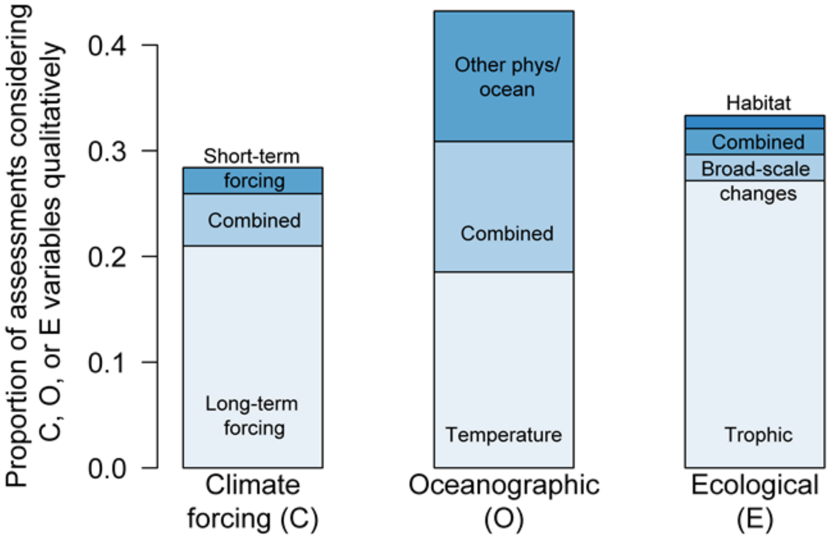

Figure 5. Proportion of assessments (n=81) considering climate forcing (C), oceanographic variables (O) or ecological variables (E) in broad-scale hypotheses or conceptual mechanisms. Within each category (C, O, and E), variables are further divided into sub-categories including combinations of sub-categories ("Combined").

Q2 – QUANTITATIVE ANALYSES

2. (a) Does the stock assessment quantitatively include climate, oceanographic, or ecological variables in the population model or time-varying biological parameters thought to be related to climate or oceanographic or ecological variables?

2. (b) If climate/oceanographic/ecological variable(s) are quantitatively included, identify if either climate (C), oceanographic indices (O) or ecological indices (E) are used, or in combination.

2. (c) If climate or oceanographic or ecological variable(s) quantitatively included, identify the variable(s) or features through which the effect is evaluated.

2. (d) If time-varying parameter(s) included, identify which parameter(s).

Only 21% of the stock assessments examined (38/178) used climate, oceanographic or ecological variables in a quantitative approach. Most frequently (42%), the quantitative approach was the estimation of a time-varying parameter within a population model, which is considered a catch-all for a complex set of processes. Here, the time-varying parameter was typically natural mortality to account for predation (here considered an ecological variable), growth or catchability/selectivity to account for changes in ocean conditions (here considered an oceanographic variable because of interannual variability in these parameters; Figure 6). Worth noting were statistical relationships predicting recruitment from climate, oceanographic or ecological variables, for example as a covariate in a stock-recruitment relationship (used in 16% of cases, Figure 6). A third approach worth noting was the use of statistical approaches to predict population productivity, typically spawning stock biomass from climate, oceanographic and/or ecological variables (also used in 16% of cases, Figure 6). In most of those instances, an assessment of habitat availability, mainly based on bottom temperature, was linked to productivity or biomass estimation of the stock or year-class.

Most commonly, the quantitative approach included either estimating a parameter within the stock assessment model, applying parameter bounds or averaging a parameter over a specified time period given information on climate, oceanographic or ecological variability over that period (14/38; Table 2). Univariate statistical approaches were also commonly used (11/38) and were typically linear regression or correlation analysis linking climate, oceanographic or ecological variables to a population attribute, for example recruitment or to an assessment attribute, e.g., for CPUE standardization within the stock assessment (Table 2). Multivariate statistical analyses, including multiple linear regression, generalized additive models, and principal components analysis were applied to provide estimates of productivity, recruitment and spawning attributes with climate, oceanographic and/or ecological variables (8 /38; Table 2). Quantitatively including climate, oceanographic or ecological variability was also accomplished with sensitivity analyses accompanying assessments, mainly for evaluating or revising harvest strategies (Table 2).

A higher proportion of stock assessments in the Pacific (34%), Maritimes (30%) and Gulf (27%) regions quantitatively included climate, oceanographic or ecological variables (Figure 7) than for other regions where less than 15% of the stock assessments included these variables quantitatively (Figure 7). Within the Pacific region, those stock assessments were predominantly (82%) for anadromous species (i.e. Pacific salmon); in the Maritimes region, those stock assessments were mainly (88%) for invertebrate species (e.g. crabs); and in the Gulf region, those stock assessments were all (100%) for groundfish species. It is these three region-specific taxonomic groupings that drive the overall pattern within DFO: anadromous, invertebrate and groundfish species stock assessments were the most frequent to have quantitative inclusion of climate, oceanographic or ecological variables (42%, 24% and 24% respectively; Figure 7).

When stock assessments did include climate, oceanographic or ecological variables in a quantitative approach, the majority included oceanographic (61%) or ecological (53%) considerations, while only 24% included climate forcing variables (Figure 8). Temperature (i.e. bottom temperature or sea surface temperature (SST)) accounted for more than half of instances when an oceanographic variable was applied, either as the only variable or in combination with other oceanographic variables (Figure 8); this was mainly applied in the anadromous species stock assessments in Pacific region (i.e. Pacific salmon) and Central and Arctic region (i.e. Arctic Char), but also to invertebrate species in either Newfoundland region or Maritimes region. Ecological variables were most often incorporated in stock assessments, as trophic interactions (31%, Figure 8), either as prey or predator abundance, but more often indirectly with time-varying natural mortality estimates to account for predation impacts. This ecological approach was most common in groundfish stock assessments in the Gulf region. Broad-scale ecological change was also indirectly included (21%, Figure 8), namely as rationale for varying productivity or recruitment.

Climate forcing was included quantitatively with the inclusion of indices characterizing short-term climatic processes (namely El Niño-La Niña Southern Oscillation [ENSO] events) and long-term atmospheric forcing (Figure 8). Accounting for long-term atmospheric forcing was more prevalent than short-term climatic processes (Figure 8). Not surprisingly, given that ENSO events occur in the equatorial Pacific, ENSO indices were only included in Pacific region stock assessments and then mainly for anadromous species (3 of 4 assessments). It is likely that ENSO indices are not included in more Pacific stock assessments because the teleconnection patterns to the Pacific region are well captured in sea surface temperature time-series. Long-term atmospheric forcing was quantitatively included most often in the Pacific region anadromous stock assessments (4 of 8 assessments) using the Pacific Decadal Oscillation index (PDO). Other large-scale indices used included the Arctic Oscillation and North Atlantic Oscillation indices (in Central and Arctic region for Arctic Char) and Atlantic Multi-decadal Oscillation index (in the Maritimes region for American Lobster).

It is interesting to note that of those stock assessments that included climate, oceanographic or ecological variables in a quantitative approach, a high proportion (87% or 33/38) provided science advice that was based on that quantitative inclusion. This might suggest that when quantitative analyses are undertaken, the inclusion of climate, oceanographic or ecological variables provides useful management advice. However, it is equally plausible that attempts to quantitatively include those variables are only reported in a stock assessment document when results are statistically significant or reduce uncertainty, thereby improving advice.

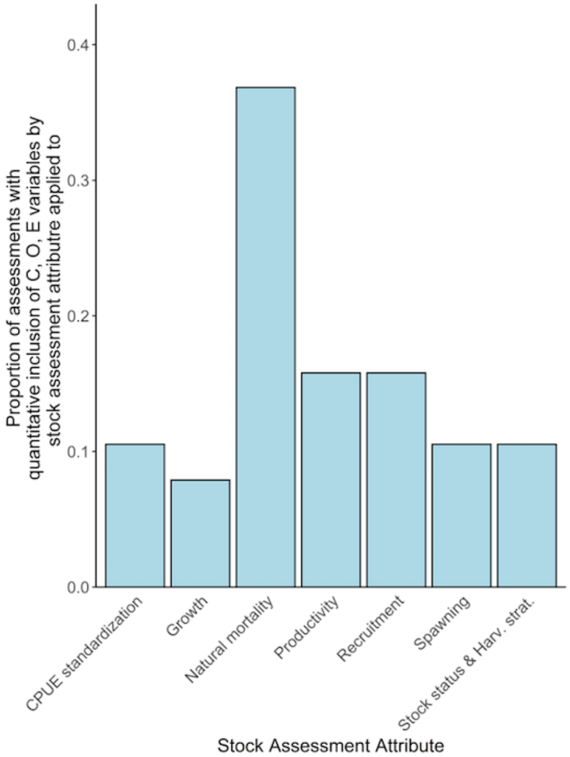

Figure 6. Proportion of stock assessments quantitatively including climate, oceanographic or ecological variables (n=38) by the stock assessment attribute to which the approach was applied to. CPUE standardization: variables used to tune fishery or survey indices of abundance, including time-varying catchability/selectivity; Growth: time-varying or period averaging estimation; Natural Mortality: time-varying or period averaging estimation; Productivity: variables used to estimate population overall productivity or abundance; Recruitment: variables used, often in a stock-recruitment relationship, to estimate recruitment; Spawning: variable used to estimate timing, migration or habitat for spawning; Stock status and Harvest strategies: variables used to adjust harvest rates, biological benchmarks or outline other harvest strategies.

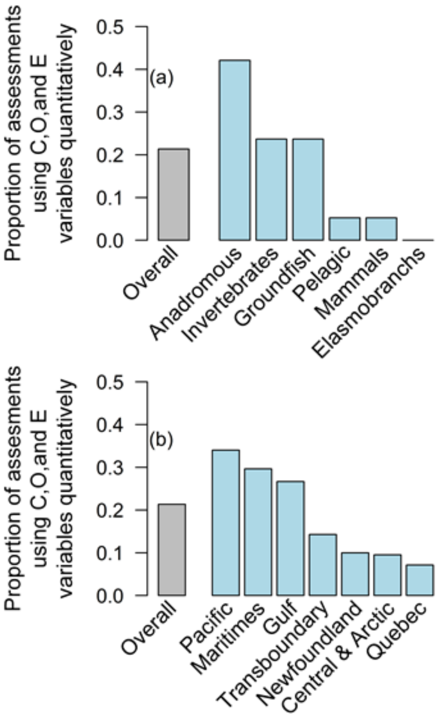

Figure 7. Overall proportion overall of stock assessments considering climate forcing (C), oceanographic (O), and/or ecological (E) variables in quantitative analyses is shown in grey bars (38/178). Blue bars indicate the proportion by (a) taxonomic groups and (b) regions. Several assessments included multiple regions, and were therefore were included multiple times in (b).

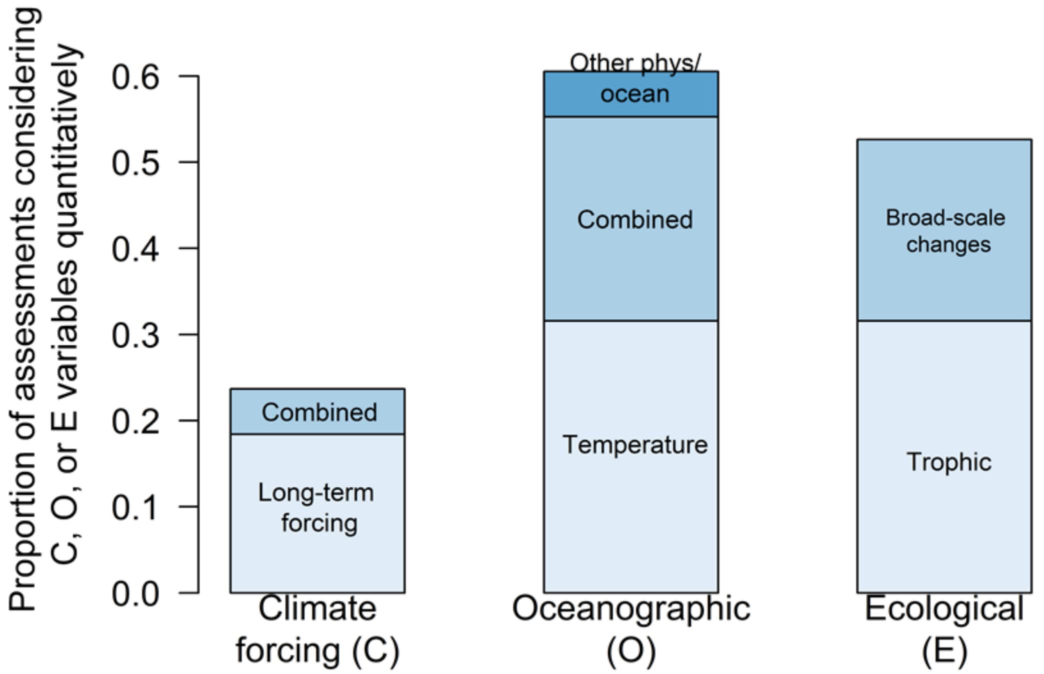

Figure 8. Proportion of assessments (n=38) considering Climate Forcing (C), Oceanographic variables (O) or Ecological variables (E). Approximately a third (32%) of these assessments quantitatively used variables from multiple categories, i.e. C, O and/or E. Within each category (C, O, and E), variables are further divided into sub-categories. Within each category (C, O, and E), variables are further divided into sub-categories. The Combined sub-category represents instances where both sub-categories were applied in a stock assessment. For Climate Forcing, the combined sub-category reflects both Long-term and Short-term forcing variables; Short-term term forcing variables were never applied as stand-alone but rather always in combination with Long-term forcing variables. The Trophic sub-category in Ecological includes assessments with time-varying biological parameter estimation to account for trophic impacts such as predation.

Table 2. Summary of methodological approaches used to quantitatively include climate (C), oceanographic (O) or ecological (E) variables into some attribute of a stock assessment. Abbreviations: AMO – Atlantic multi-decadal oscillation; ENSO – El Niño Southern Oscillation; NPGO – North Pacific Gyre Oscillation; PDO – Pacific Decadal Oscillation; SSS – Sea Surface Salinity; SST – Sea Surface Temperature. Numbers in parentheses indicate number of stock assessments employing methodological approach.

Assessment Attribute	**Methodological Approach**	**Examples of C, O or E variables employed**
CPUE standardization	• applying statistical approaches such as analysis of variance (ANOVA), correlation and regression analyses with CPUE or with catchability to adjust for conditions (3)	temperature
-	• time-varying catchability parameter in model (1)	-
Growth parameter	• periods of different growth applied in model either as multi-year average (1)	-
	• time-varying growth estimated in the model (2)	-
Harvest strategies	• sensitivity analyses included revised biological benchmarks that accounted for reduced productivity (2)	-
-	• sensitivity analysis, time-varying productivity parameter included in to evaluate harvest strategies in simulation (1)	-
-	• multivariate analyses (Principal Component Analysis, PCA) on oceanographic and ecosystem status produce ecosystem contextual indicators used to alter harvest rates (1)	temperature oxygen sea ice prey/predator abundance
Natural mortality parameter, M	• time-varying annual M estimated by a population model (6)	-
-	• periods of different M applied in model either based on conditions, or as multi-year average (3)	sea ice
-	• M due to predation in Bayesian surplus production model to provide sensitivity run (1)	predator abundance
-	• linear regression analysis predicting M (2)	NPGO, ENSO, PDO, SST, SSS
-	• periods of different M identified based on observed conditions (1)	SST, SSS
-	• time-varying M estimated from predation proxy and used in model (1)	-

Assessment Attribute	**Methodological Approach**	**Examples of C, O or E variables employed**
Productivity estimates	• multivariate analyses (PCA, Generalized Additive Model, GAM) to estimate population productivity or spawning stock biomass (2)	temperature ice
-	• correlation analysis to estimate production based on climate and prey indices (1)	prey abundance unspecified composite climate index
-	• multiple indicator diagnostic approach (1)	temperature predator abundance
-	• multivariate analyses (PCA) to produce ecosystem contextual indicators that augment other stock status indicators for data-limited stocks (1)	AMO temperature predator abundance
-	• habitat suitability incorporated into state-space model which produces biomass estimates and projections (1)	bottom type
Recruitment estimates	• Bayesian multiple linear regression to forecast recruitment (1)	PDO, NPGO
-	• covariate in stock-recruitment model (4)	PDO, SST, SSS, predation proxy
-	• linear regression analysis to forecast recruitment (1)	temperature
Spawning migration or timing estimates	• statistical analyses, (multiple linear regression, linear regression, GAM) (3)	SST, SSS, current, ENSO, PDO, discharge
-	• frequency analysis of historic data used to identify environmental characteristics that are then applied to current data to inform migration forecasting (1)	temperature discharge

Q3 – QUALITATIVE INTERPRETATION

3. (a) Does the stock assessment qualitatively include climate or oceanographic variables, or ecological variables when interpreting status and trends?

3. (b) If (a) is yes, identify if either climate (C), oceanographic indices (O) or ecological indices (E) are used, or a combination.

3. (c) If (a) is yes, identify the specific climate, oceanographic or ecological indices used.

3. (d) If (a) is yes, identify how they were qualitatively included. For example, but not limited to:

- A stoplight approach which provides indication of relative year-class strength;
- Using information on climate or oceanographic conditions to interpret trends or anomalies in indices of abundance or in stock assessment model outputs. This might include the mediation of impacts of changes in climate or oceanographic conditions through ecological drivers (such as change in prey or predation).

We found that 31% (55/178) of stock assessments qualitatively considered climate, oceanographic or ecological variables when interpreting status or trends. Climate, oceanographic and ecological variables were most frequently used to explain historical trends in biological processes (e.g., abundances, growth, maturation, and distribution from habitat suitability models), although these were also used to explain anomalies in specific years, explain the current status, account for uncertainties in assessments, and forecast future status and trends (Figure 9).

These variables were most often considered qualitatively for anadromous species (46% of assessments included them) and relatively infrequently for groundfish, mammals, and elasmobranchs (22%, 21%, and 14%, respectively) (Fig. 10). This percentage varied among regions, with stock assessments from the Gulf region having the highest (39%) and those from the Central and Arctic having the lowest (17%) (Figure 10).

Among stock assessments with positive responses to question 3a, 27% considered climate forcing, 73% oceanographic variables, and 62% ecological variables. Among climate variables, long-term atmospheric forcing (e.g., PDO, NAO) was considered more often than short-term climatic processes (e.g., El Niño) in qualitative interpretations of status and trends (Figure 11). Among oceanographic variables, temperature was the dominant factor considered. Trophic interactions (e.g., predation, competition) were a common ecological consideration, but broad-scale changes in productivity and habitat were also considered (Figure 11).

While oceanographic variables were most frequently considered across most taxonomic groups in qualitative considerations, ecological variables were more frequently considered for groundfish (used in 10/19 assessments that included qualitative considerations). Climatic forcing was more frequently considered in assessments for anadromous species than for other species (8/21 assessments for salmon). Oceanographic variables were more often considered than climate or ecological variables for most regions, but ecological variables were more frequently considered for Maritimes region (10/19 assessments). Climate forcing was more frequently considered in assessments in Pacific region (8/22 assessments) than in other regions.

Of those assessments that included qualitative considerations, 45% of them also considered climate, oceanographic or ecological variables in quantitative assessments and 65% of qualitative assessments used that information to provide management advice.

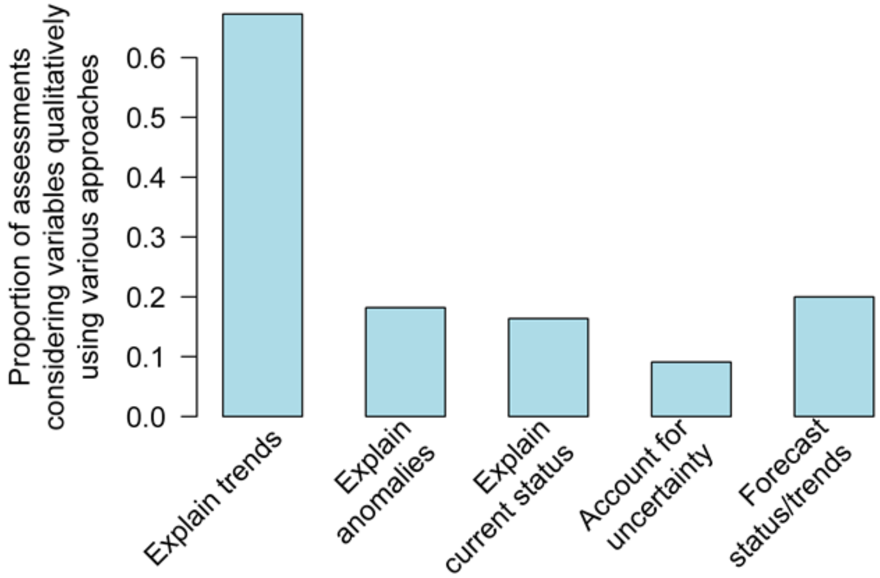

Figure 9. Proportion of stock assessments qualitatively including climate, oceanographic or ecological variables (n=55) using various qualitative approaches for considering climate, oceanographic or ecological variables. Multiple assessments used numerous approaches.

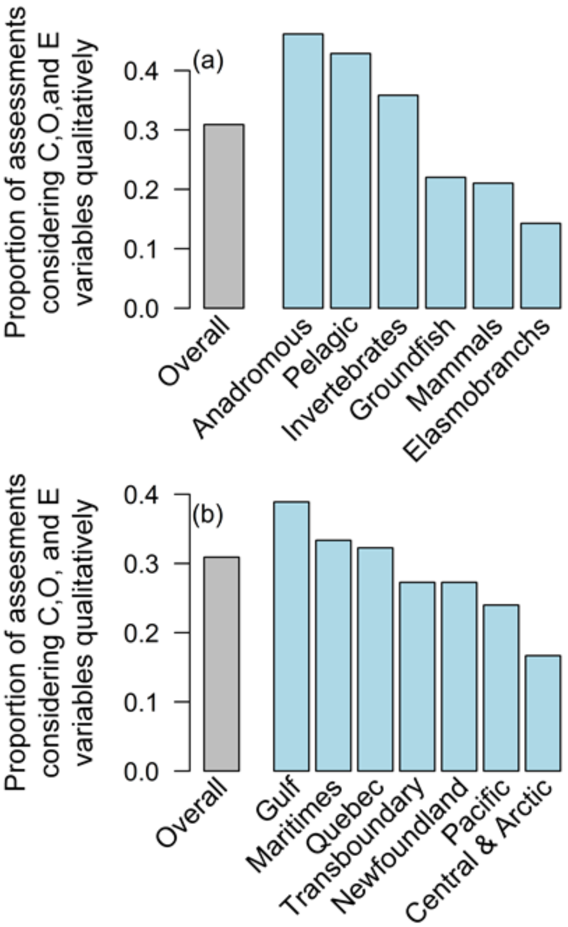

Figure 10. Overall proportion overall of stock assessments considering climate forcing (C), oceanographic (O), and/or ecological (E) variables in qualitative interpretation is shown in grey bars (55/178). Blue bars indicate the proportion by (a) taxonomic groups and (b) regions. Several assessments included multiple regions, and were therefore were included multiple times in (b).

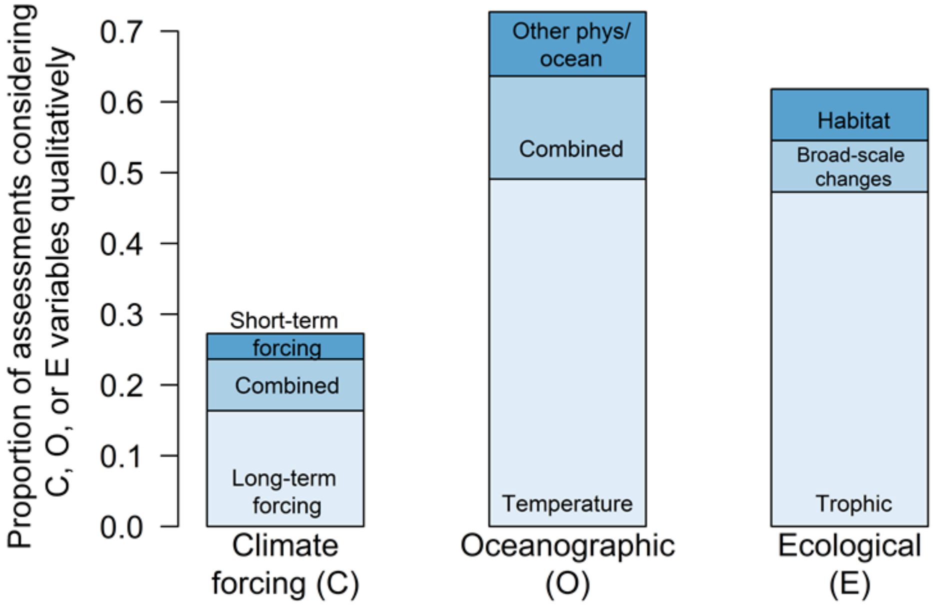

Figure 11. Proportion of positive assessments (where the response to Q3a was "yes", n=55) considering climate forcing (C), oceanographic variables (O) or ecological variables (E). A large proportion of assessments consider variables from multiple categories. Within each category (C, O, and E), variables are further divided into sub-categories, including those that used variables from a combination of sub-categories ("Combined"). See text for explanation of sub-categories.

Q4 – RECOMMENDATIONS AND ADVICE

4. (a) Did the final, or recommended, advice provided in the stock assessment include climate or oceanographic or ecological considerations? Many stock assessments might have aspects that fulfill the questions above, but in the final recommended harvest rate not utilize those analyses.

4. (b) if (a) is yes, identify if either climate (C), oceanographic indices (O) or ecological indices (E) are used, or a combination.

4. (c) If so, identify how the advice included climate or oceanographic or ecological considerations? For example but not limited to:

- recommended harvest rates based on a population model run that included climate or oceanographic variables (i.e. analyses contained in question 2 above)
- recommended harvest rates based on assumptions regarding population dynamics as informed climate or oceanographic variables (i.e. analyses contained in question 3 above)
- management strategy evaluation has been used to outline harvest strategies that are robust to impacts on population dynamics due to observed or expected climate or oceanographic variability

4. (d) If not, identify why the advice did not include climate or oceanographic or ecological considerations?

Of the 178 assessments evaluated in our analysis, 48 (27%) made recommendations or provided advice based on climate or oceanographic or ecological considerations, which represents a substantially lower number than the documents that identified hypotheses or broad-scale conceptual mechanisms that link climate, oceanographic or ecological forcing to population dynamics (81). However, approximately one quarter (11) of these 48 assessments did not actually identify hypotheses or conceptual mechanisms as the basis for the assessments. This may represent a gap in knowledge in which associations with environmental conditions emerge from exploratory analyses (i.e., they were not present at the outset), or instances where underlying knowledge served to interpret changes in life history features based on oceanographic or ecological considerations. This lack of clarity points to a need to fully document all hypotheses or conceptual mechanisms in the stock assessment document.

Thirty-three (33) assessments incorporated quantitative evaluations or analyses of the relationship between stock status and climate, oceanographic and ecological variables (question 2a), and represented 69% of the assessments with positive responses to 4a. Thirty-six (36) of the 48 assessments included qualitative interpretations of the relationships between stock status and climate, oceanographic and ecological variables (question 3a, 75%). More than half of the instances with recommendations that included oceanographic or ecological considerations (61%) were based on instances where both quantitative and qualitative results were applied in the interpretation of population change.

The occurrence of climate, oceanographic and ecological variables in advice was greatest in salmonids and other anadromous species (58%), with the predominance in Pacific salmon species (Figure 12). Thirty-six percent (36%) of assessments of pelagic stocks had climate, oceanographic and ecological considerations in their assessments while twenty-six percent (26%) of shellfish and marine mammal assessment had recommendations/advice based on features of the environment. Only fifteen percent (15%) of groundfish stock assessments had climate, oceanographic and ecological considerations in the advice, while these appeared in none of 7 assessments for elasmobranchs. The contrast among taxa may be partly a reflection of the extent of variations in environmental conditions likely to be encountered in the upper water column, but they may also reflect differences in longevity of the different taxa. Differences in the history of the different ecosystems, such as the collapse of the Atlantic of cod and other groundfish in the late 1980s and early 1990s, may also contribute to the differences. Assessments in the Maritimes and Pacific regions had the highest proportion of assessments with recommendations that involved climatic, oceanographic or ecological considerations, followed by Gulf and Quebec (Figure 12).

Climate considerations appeared in 18% of the 48 assessments in which environmental conditions were included in the advice, and generally in combination with oceanographic and ecological considerations. Overall, oceanographic variables appeared in 73% of these assessments and 71% for ecological considerations. In relative proportions, climate considerations appeared in fewer of the recommendations than in the conceptual, quantitative and qualitative aspects of the assessments.

Approaches for including environmental variables in advice

Environmental considerations (climate, oceanographic, or ecological variables) were used in the advice relevant to harvest control rules in 43 of the 48 assessments (90%). Time-varying parameterization or interpretation of population life history features, principally in terms of changes in natural mortality rates, occurred in 31% (15/48) of these assessments. The link between population trends and climate, oceanographic and ecological variables was noted in 14% (7/48) of assessments, and generally served to explain expectation of future population state and production potential, which were often linked to the trends in other elements of the food web. Climate, oceanographic and ecological considerations were identified as a source of uncertainty in 4 of 49 assessments and occurred as contextual information pertinent to recommendations about harvest control rules.

Of the 130 assessments where climate, oceanographic and ecological considerations were not included in the recommendations, 64 did not include a section pertaining to variations in climate, oceanographic or ecological conditions despite many of them (44) having explicitly identified hypotheses or broad-scale conceptual mechanisms that linked climate, oceanographic or ecological forcing to population dynamics somewhere in the assessment. In 26 of the remaining 66 assessments with no climate, oceanographic or ecological based recommendations, a lack of clear understanding of the mechanisms by which environmental conditions would affect the population was cited as the reason for not providing advice about climate, oceanographic and ecological variables. Data limitations or uncertainty were cited in 30 of 66 assessments as the reason for the lack of consideration of climate, oceanographic and ecological variables in the advice, with only 4 of those assessments also having cited a lack of understanding about mechanisms for effect on the interpretation or forecasting of population trends. Eleven (11/66) assessments identified other factors as having a greater influence on populations than climate, oceanographic and ecological variables; 6 documents cited fishing or bycatch as important drivers of population status; 2 raised issues of data quality pertaining to the assessment itself; 1 indicated that habitat availability was likely key to stock status; 1 cited the breakdown of a previous environmentally-based relationship; and 1 indicated that low stock abundance was likely the greatest limitation to population growth although environmental conditions likely will play a more important role if recovery occurs. A lack of quantifiable benefit to the analysis or projection of stock status was cited in 11 of 66 assessments. Finally, in one assessment no reason was given for the lack of consideration for environmental data despite citing several studies that ocean conditions would affect release mortalities in other areas where the species is harvested.

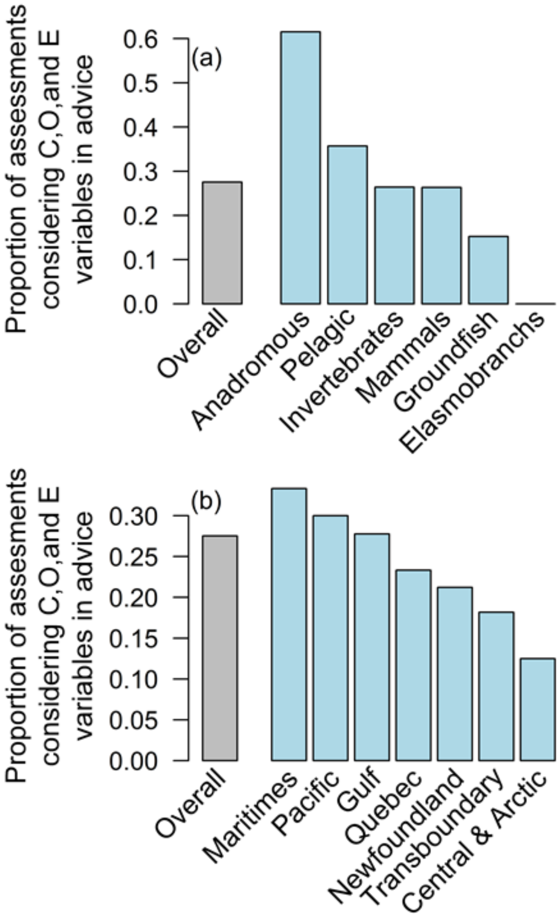

Figure 12. Overall proportion overall of stock assessments considering climate forcing (C), oceanographic (O), and/or ecological (E) variables in in management advice is shown in grey bars (48/178). Blue bars indicate the proportion by (a) taxonomic groups and (b) regions. Several assessments included multiple regions, and were therefore were included multiple times in (b).

RESULTS – GLOBAL PERSPECTIVE

1. Focus on global examples for which the final, or recommended, advice provided in the stock assessment included climate, oceanographic or ecological considerations. This section cannot be exhaustive, so will not include the examples where the conceptual mechanisms are identified, where indices are quantitatively or qualitatively included if the final advice did not use that information.
2. Jurisdictions to include:
    a. USA
    b. Australia
    c. International Council for the Exploration of the Seas
    d. South Africa
3. Brief summary that identifies common elements, and identify if a national or regional strategy exists for including climate change into stock assessments.

STOCK ASSESSMENTS

United States (USA)

The USA has made considerable progress in the quantitative and qualitative incorporation of climate, oceanographic and ecological variables (or combinations thereof) into fisheries management advice. Using the same analysis as for the Canadian assessments, we noted that climate, oceanographic and ecological variables were included in the final advice provided in 7 stock assessments including Pacific Sardine (*Sardinops sagax*, SST*)* (Hill, Crone et al. 2017)*,* Arrowtooth Flounder (*Atheresthes stomias*, bottom temperature) (Spies, Wilderbuer et al. 2016), Pink salmon (*Oncorhynchus gorbuscha*, temperature index) (Wertheimer, Orsi et al. 2015), Pacific Cod (*Gadus microcephalus*, SST and NPI) (Thompson 2017), Eastern Bering Sea stock of Walleye Pollock (*Gadus chalcogrammus*, SST and Ecosystem Report) (Ianelli, Kotwicki et al. 2017), Black Sea Bass (*Centropristis striata*, bottom temperature and salinity) (Northeast Fisheries Science Centre 2017a) and Butterfish (*Peprilus triacanthus*, SST) (Northeast Fisheries Science Center 2014). Of these 7 stocks assessments, all identified hypotheses or broad-scale conceptual mechanisms that link climate, oceanographic or ecological forcing to population dynamics. Oceanographic variables were considered either on their own (3/7), with climate variables (1/7), with ecological variables (1/7) or as a joint consideration with oceanographic, climate and ecological variables (2/7). Ecological variables were considered in 3 stock assessments with oceanographic variables (1/7), or with both climate and oceanographic variables (2/7). Climate variables were considered in 3/7 of stock assessments, never on their own (0/7), with oceanographic variables (1/7), or with oceanographic or ecological variables (2/7). All 7 stocks used variables quantitatively, either with (29%) or without (71%) qualitative indicators. It should be noted that the National Marine Fisheries Service (NMFS) does track assessments currently using ecosystem considerations quantitatively in the stock assessment models (P. Lynch, *pers. comm*), which are: Red grouper (*Epinephelus morio*, Gulf of Mexico); Butterfish (*Peprilus triacanthus*, Gulf of Maine / Cape Hatteras); Atlantic herring (*Clupea harengus*, Northwestern Atlantic Coast); Arrowtooth flounder (*Atheresthes stomias*, Bering Sea / Aleutian Islands); Flathead sole (*Hippoglossoides elassodon*, Bering Sea / Aleutian Islands); Yellowfin sole (*Limanda aspera*, Bering Sea / Aleutian Islands); Sablefish (*Anoplopoma fimbria*, Eastern Bering Sea / Aleutian Islands, Gulf of Alaska); 4 stocks of Chinook salmon (*Oncorhynchus tshawytscha*, Puget Sound and Washington Coast regions), and ; 8 stocks of Coho salmon (*O. kisutch*, Oregon, Puget Sound and Washington Coast regions).

Quantitative oceanographic variables included temperature (sea surface, bottom and air) in all cases, salinity (3/7), oxygen (1/7), and mixed layer depth in 1/7 of assessments. The incorporation of temperature was high in both the Atlantic and Pacific stock assessments. Quantitative climate variables in 1/7 cases included the PDO winter index and multivariate ENSO, whereas the North Pacific Index (Trenberth and Hurrell 1994) was incorporated in 2 assessments. No quantitative climate variables were applied to Atlantic species. Ecological quantitative indicators included zooplankton indices, chlorophyll levels, nutrients and predation indices, and were incorporated in 1 of the cases. Ecological quantitative indicators were only applied for East Bering Sea Walleye Pollock.

The management of Pacific Sardine is perhaps one of the most sophisticated integrations of oceanographic variables into fisheries management (Hill et al. 2017). Here, the harvest control rule and allowable biological catch directly includes a temperature-driven uncertainty buffer (E_{msy}), which is based upon a three-year average of sea surface temperatures of the California Current (CalCOFI) system. The fisheries management of this species is further enhanced by spatial regional models. The J-SCOPE spatial model (JISAO'S Seasonal Ocean Prediction of the Ecosystem) provides projections of physical, chemical and biological properties on 6- 9 month time horizons, and is designed to be relevant for tactical management decisions (Kaplan et al. 2016). This model is based on the climate forcing as specified by the Climate Forecast System atmosphere-ocean-land model that assimilates both *in situ* and satellite-based ocean and atmospheric data (Saha et al. 2006, Saha et al. 2010), which is then applied regionally using Regional Ocean Modelling Systems (ROMS) and includes 17 river discharges. Other model parameters predicted by the ROMS and CFS models are sea surface salinity, chlorophyll, nutrients and oxygen. Zooplankton productivity is also included. The J-SCOPE model then uses generalized linearized models to predict 4-8 months in advance the spatial distribution of sardine stocks. Although the application of this model would have obvious value to predict catchability, it is not specifically mentioned in the 2017 Pacific Sardine stock assessment (Hill et al. 2017), but may have been used in assessment discussions (see *National and Regional strategies*).

Qualitative interpretations were applied in 2/7 cases; Southeast Alaska Pink salmon and Walleye Pollock from the Eastern Bering Sea stock. In these cases, the indices were linked to a hypothesized increase in predation (Pink salmon), and predator prey-relationships (Walleye Pollock). More generally for US stock assessments qualitative approaches are more broadly applied in the form of Ecosystem Status Reports. These reports provide contextual information for informed decision-making by resource managers, i.e. a qualitative approach for including climate, oceanographic and ecological variables into stock assessment. These Ecosystem Status Reports are produced for the Northeast (Ecosystem Assessment Program 2012), California Current (Levin et al. 2013), Gulf of Mexico (Karnauskas et al. 2017), Alaska (Whitehouse and Zador 2016, Zador 2016, Siddon and Zador 2017, Zador and Yasumiishi 2017) and West Hawai'i (PIFSC 2016). Information contained within these reports can include large-scale climate-related oscillations (e.g. PDO, ENSO, NAO, AMO, North Pacific Gyre Oscillation), sea ice cover, SST, plankton productivity, environmental stressors, acoustic estimates, biomass of epifauna and foragers, predator biomass, seabird breeding index, marine mammal production, ocean acidification, oxygen / hypoxia, seafloor habitat disturbance as well as socio-economic indicators. This allows tailoring of applications from larger scales to local resource management. However, the development of such large, complex Ecosystem Status Report advice with indicators on socio-economic, biological, physical and chemical aspects of ecosystems is not without challenges (Slater et al. 2017). Challenges include insufficient staff time and limited resources, issues of spatial and temporal relevance, data management, timing of the report release, and the difficulty of strategically updating the reports. Furthermore, many of these issues are considered in terms of the consistency in the trends rather than causal relationships *per se*.

The Alaska Ecosystem Status Reports are produced annually with separate reports for Eastern Bering Sea (2017), Aleutian Islands (2016), Gulf of Alaska (2017) and Arctic (forthcoming, most recent 2015) ecosystems. This report and a summary report card are then provided to the North Pacific Fishery Management Council for contextual decision-making. For example, information in the 2008 Ecosystem Consideration report (Boldt 2008) supported a significant reduction in total allowable catch of Eastern Bering Sea Walleye Pollock from the maximum allowable, which was estimated by the stock assessment model (North Pacific Fishery Management Council 2007). Ecosystem considerations used to support this decision included 4 years of below average recruitment, a northward population shift, low abundance of forage fish and zooplankton prey and increased predation by Arrowtooth flounder (Boldt 2008). The California Current Integrated Ecosystem Assessment is also updated annually, providing 'Indicator Status and Trends' information, providing indicator data and 5-year trends for specific stocks such as groundfish and salmon, and includes climate and ocean driver data as well as ecological integrity indicators (National Oceanic and Atmospheric Administration 2018). The Pacific Fishery Management Council developed a Fishery Ecosystem Plan for the U.S. portion of the California Current (Pacific Fishery Management Council 2013), which contains climate impacts on resources and consideration of ecosystem considerations into stock assessments.

Ecosystem-based fisheries management (EBFM) can explicitly account for environmental changes and make trade-off decisions for actions that impact multiple species, including ecosystem processes and drivers such as climate change. NOAA's EBFM Road Map (Sagar et al. 2016) incorporates vulnerability assessments, development of a Management Strategy Evaluation capable to conduct ecosystem-level analyses, with the aim of incorporating ecosystem considerations into Living Marine Resources (LMR) stock assessments with exploration of trade-offs within a given region. The EBFM is complimentary to the National Oceanic and Atmospheric Administration (NOAA) Fisheries Climate Change Strategy and will support and integrate ongoing analytical and management efforts in each region to ensure that national efforts are reflective of the local knowledge resulting from regional science, management, and stakeholder approaches (Sagar et al. 2016).

Australia

Australia has demonstrated success in incorporation of climate, oceanographic and ecological variables into predictive stock management and the development of spatial models. The Rock Lobster (*Panulirus cygnus*) has both climate and oceanographic variables quantitatively included in the management of West Coast Rock Lobster Managed Fishery, the Augusta-Windy Managed Fishery and the South Coast Crustacean Fisheries stocks (de Lestang et al. 2012). In this case, harvest rates are based on climate phenomena (ENSO-related Southern Oscillation Index (SOI), which then influences the Leeuwin Current), rainfall (used as a proxy for frequency of western winds), sea level height and sea surface temperature (SST). The stock recruitment relationship was calculated as function of the Leeuwin current, SST related to juvenile lobster recruitment, and SST related to catchability and used to project catches 3-4 years into the future for more sustainable management. Climate, oceanographic and ecological variables have been quantitatively applied to the management of another invertebrate, the Torres Strait Sea cucumber *Holothuria scabra* in northern Australia (Plaganyi et al. 2013). SST, sea levels, changes to current systems, rainfall, ocean acidification, habitat and phytoplankton productivity were used to generate risk rankings (low, medium, high) in the context of 2030 projections (under mid-high range Intergovernmental Panel on Climate Change (IPCC) scenario), considering life history variables for three life stages; these were then incorporated into the MSE in the operating model. This study demonstrated the use of spatial MSE to test the performance of alternative harvest strategies through climate variability and change.

Predictive spatial models for Bluefin Tuna have been developed in the Great Australian Bight region of Australia (Hobday et al. 2011, Eveson et al. 2015) and provide in-season advice on harvest locations. A combination of climate, oceanographic and ecological variables were used to create a regional spatial tool to improve catchability, which is available on-line and with a predictive capacity of 0-2 months. For current conditions, SST (uppermost 15m layer) is measured by satellite along with SynTS (which uses CTD and Argo float data) for nowcasts, and then predictively forecasted by the Predictive Ocean Atmosphere Model for Australia (POAMA) climatology model through predictions of ENSO SST. The BRAN (BLUElink Ocean Reanalysis) model is then used to create a 10km SST grid for ocean circulation patterns and a habitat model based on tagging studies then defines the predicted tuna locations for capture under allowable catch. Species range shifts and associated catchability are important considerations for fisheries management in future climates, and local economies.

International Council for the Exploration of the Sea (ICES)

Examples of the incorporation of climate, oceanographic or ecological variables to fisheries management are limited in Europe. However, the ICES (International Council for the Exploration of the Sea) Working Group on Seasonal-to-Decadal Prediction of Marine Ecosystems (2017-2020) are working to address this and will be generating forecast products covering both seasonal and out to decadal time scales. Under this initiative, a stock assessment for Blue Whiting (*Micromesistius poutassou*) was recently developed and updated (Payne 2018). Model components include using oceanographic (salinity, oceanographic profile), climate (solar elevation) and ecological (larvae from Continuous Plankton Recorder, day-of-year, depth) variables to generate a forecast with lead-times of two months. Forecast skill assessment lead-times were up to 2-3 years. Ecosystem changes in the Baltic Sea have been considered analytically in the following stock assessments: Herring in SD 25–27, 28.2, 29 and 32, and Sprat in SD 22–32, in the form of cod predation mortality (ICES 2017a).

Previously ICES had applied an oceanographic variable to Bay of Biscay Anchovy (*Engraulis encrasicolus*) fisheries management, by predicting recruitment based on a strong correlation ($r^2 = 0.7$) of an upwelling index to a long time-series of recruitment data based on Catch Per Unit Effort (CPUE) for 1967-1996 (Borja et al. 1996, 1998); this relationship was confirmed in assessments. However, in 2000 the spawning stock biomass based on this prediction resulted in a significant reduction of total allowable catch, which was thought to be related to environmental conditions. The subsequent assessment (ICES 2001) shows a large underestimation of biomass had occurred in the previous year and therefore an upward adjustment of spawning biomass was made. A second index relating environment with anchovy recruitment was compared to the previous model, which incorporated a 3D hydrodynamic physical model and a Stratification breakdown index (SBD) in addition to an upwelling index (Allain, Petitgas et al. 2001). These two environmental models were applied against recruitment estimates from the 2000 assessment, which reduced the variance explained by the Borja upwelling index to 5.5% (not significant), and to 40% (still significant) for the Allain index (postulated SBD an important effect). Whilst the ICES Working Group recognized that a reliable environmental index would be invaluable, the imprecise nature of the indices would not allow reliable recruitment forecasts and these indices were therefore not used in the stock assessment (ICES 2001). In 2005 it was again noted that recruitment is likely to be strongly dependent on environmental factors, but environmental indices were not significantly accurate to estimate the population a year in advance (ICES 2005). Therefore, even strong correlations to oceanographic conditions with data-rich fisheries information can lead to incorrect assumptions on drivers of fisheries abundance.

International Stocks

A number of fisheries stocks are managed internationally, such as the International Commission for the Conservation of Atlantic Tunas (ICCAT) Bluefin Tuna (*Thunnus maccoyii*) and Atlantic Swordfish (*Xiphias gladius*) stocks (Commission for the Conservation of the Southern Bluefin Tuna 2016, ICCAT Secreteriat 2017a, ICCAT Secreteriat 2017b). The Atlantic Swordfish management quantitatively included climate (AMO), oceanographic (temperature, depth, oxygen) and ecological (chlorophyll) variables to predict north-south seasonal migrations and included them in model catchability (ICCAT Secreteriat 2017a). Future recommendations to increase predictive capacity included better time-varying data. For the Southern Bluefin Tuna, the standardization of a grid-type trolling index (GTI) of age-1 tuna with environmental factors was proposed to develop a robust indicator of recruitment (Commission for the Conservation of the Southern Bluefin Tuna 2016). Climate (rainfall, wind, sunshine, air temperature) factors were quantitatively applied to a GLM model; weather conditions were found to have no affect and therefore the GTI was applied to stock assessments without the inclusion of weather factors. The Commission (Commission for the Conservation of the Southern Bluefin Tuna 2017) specifically recommended research on the impact of climate change on tuna reproduction and recruitment (medium / high priority), but this did not appear on workplans for 2018-2020 (Commission for the Conservation of the Southern Bluefin Tuna 2017). A recommendation to identify environmental factors related to catchability at basin and local scales was noted, to incorporate into a standardized index, as well as impacts on spawning (ICCAT Secreteriat 2017b).

Summary

Of the case studies highlighted, the majority use temperature as a dominant oceanographic variable and the inclusion of climate variables (e.g. ENSO, North Pacific Index) has led to the development of a number of spatial models of catchability for migrating or range-shifting species. Caution is to be used when applying single drivers to causal effects, as strong correlations may not capture underlying mechanisms driving population abundances.

NATIONAL AND REGIONAL STRATEGIES OF CLIMATE CHANGE CONSIDERATIONS AND ADAPTATIONS IN FISHERIES MANAGEMENT

As a second part of our global assessment, we searched for regional or national strategies of climate change consideration in fisheries management in the USA, Australia, Europe (ICES), South Africa and international regulatory bodies. Whilst not all had confirmed strategies in place, each had made efforts towards that goal.

United States (USA)

Of the countries and jurisdictions examined, only the USA has a formalized strategy, the National Oceanic and Atmospheric Administration (NOAA) Fisheries Climate Science Strategy (Link, Griffis et al. 2015). The goal of this strategy is to increase the production, delivery, and use of climate-related information required to fulfill NOAA Fisheries mandates, and uses seven common objectives to meet science information requirements. These objectives are: 1) identify appropriate, climate-informed reference points for managing living marine resources (LMRs); 2) identify robust strategies for managing LMRs under changing climate conditions; 3) design adaptive decision processes that can incorporate and respond to changing climate conditions; 4) identify future states of marine, coastal and freshwater ecosystems, LMRs, and LMR-dependent human communities in a changing climate; 5) identify the mechanisms of climate impacts on ecosystems, LMRs, and LMR-dependent human communities; 6) track trends in ecosystems, LMRs, and LMR-dependent human communities and provide early warning of change; and 7) build and maintain the science infrastructure needed to fulfill NOAA Fisheries mandates under changing climate conditions. This federal NOAA overarching program will then coordinate at a more local scale to develop Regional Action Plans (RAPs) to identify strengths, weaknesses, priorities, and actions to implement the national Strategy in each region, so that the Strategy can be customized to fit regional needs and capacity (Link, Griffis et al. 2015). Within the Strategy are seven interdependent climate science strategy objectives, which are: 1) build and maintain adequate science infrastructure; 2) track change and provide early warnings; 3) understand mechanisms of change; 4) project future conditions; 5) adaptive management processes; 6) robust management strategies, and culminating with 7) climate-informed reference points. This obviously is a significant undertaking spanning both fisheries and aquaculture sectors, and hence immediate actions addressing common challenges were prioritized which, briefly, include conducting regional climate vulnerability analyses, better preparedness for tracking and response to climate change using ecosystem indicators and status reports, and development of capacity to conduct MSEs. Near-term actions include strengthening climate-related science capacity including climate-related process-orientated research, and establishing standard, climate-smart terms of reference for fisheries management.

In summary, the U.S. currently uses both national and regional climate considerations of multiple metrics and scales in both quantitative and qualitative assessments of fisheries (which includes aquaculture) resource management on single-species levels and is enhancing and accelerating the implementation of ecosystem-based fisheries management.

Australia

Commercial fishers have already observed direct impacts of climate change on Australia’s fisheries (Senate Environment and Communications References Committee 2017), but does not currently have a formalized climate change fisheries strategy, either nationally or regionally. Understanding what climate changes are occurring and being “climate ready” will allow industry and management resource planning to allow operations to avoid or mitigate negative impacts and also optimize any new opportunities that arise (CSIRO 2018). However, there is significant progress being made towards management change. Specifically: 1) risk assessments are being used for prioritization of information needs; 2) report cards provide condensed information for decision-making; 3) reviews of research impact for provision of data required for models; 4) development of adaptation options to assist stakeholder groups, and; 5) management responses (Hobday 2018). A recent sensitivity analysis has shown that 70% of all key Australian target species have moderate to high sensitivity in one of the following factors: abundance; movement and spatial distributions, and; behaviour (CSIRO 2018). Such sensitivity analysis has suggested that fisheries management should consider the effects of changes in distribution and phenology before considering possible effects on abundance in strategic planning (CSIRO 2018).

Modelling of future scenario conditions predicted that not only would there be physical changes (e.g. temperature, pH) but also that ecosystems are predicted to become more variable (for example episodes of productive years followed by very low production) (CSIRO 2018). A recent Commonwealth Scientific and Industrial Research Organization (CSIRO) Senate Inquiry submission (Hobday et al. 2016) examined the adequacy of current quota-setting given current and projected climate change impacts, and indicating that although Australia has capacity to provide information on climate change and adaption options, there needs to be a focus on policy and governance, with support from on-going research efforts. A climate robust approach to fisheries management would require a combination of information, such as those in the physical environment, satellite ocean colour, good quality catch and effort data, survey data, as well as citizen science data (CSIRO 2018). Some of the Senate's recommendations (Senate Environment and Communications References Committee 2017) following this inquiry were: 1) reviews of funding on climate change impact research and adaption measures to ensure that funding is appropriate; 2) that the Australian Government assist in industry adjustment to the effects of climate change; 3) that greater emphasis be placed on marine resource management and projects that deliver sustainable fisheries and aquaculture in the face of climate change; and 4) that Australian, state and territory governments review all environmental and resource management legislation to ensure that climate change consideration is expressly required as part of the assessment and decision-making processes. During this inquiry (Senate Environment and Communications References Committee 2017), the non-governmental Environmental Defenders Offices of Australia (EDOA) suggested that climate change impacts be mandatory consideration in decision-making under the Environment Protection and Biodiversity Conservation Act of 1999, and be incorporated throughout assessments and management plans.

The Australian Fisheries Management Authority (AFMA) is actively working to understand the threats and opportunities as a result of impacts of climate change and has recently adopted an Australian Fisheries Adaptive Management Plan as a way to combat climate impacts and build resilience in their fisheries (Burden et al. 2017). MSEs are used to conduct evaluations of entire management cycles and develop harvest strategies capable of adjusting to new information. This process can build adaptive capacity, reduce vulnerability and increase socioecological resilience while promoting sustainable fisheries (Ogier et al. 2016). There will likely be large differences between species responses and levels of effect in food webs, with predictions that demersal and invertebrate populations would be strongly affected (CSIRO 2018). Following recent sensitivity and projection analysis (CSIRO 2018), a set of management recommendations were made, which included: 1) a staged response might be necessary, where fishing is adjusted due to shifts in behaviour; 2) that not all fisheries and operators will have the same exposure to change, nor capacity to adapt, and therefore supporting information and mechanisms should be provided; 3) that successful management will be function of good scientific tools and multiple approaches, including Models of Intermediate Complexity in Ecosystems (MICE); 4) existing management strategies and objectives should be reviewed in context of long-term management responses and objectives; 5) that fisheries policy, management and assessment methods need to account for the concept of regime shifts and extreme events in contextual decision making; 6) that fisheries methods should be as flexible as possible, to respond to changing system state; 7) management needs to prioritize resources for vulnerable species; 8) nation-wide coordination to account for State and Commonwealth boundaries; and 9) need to use integrated marine management. Integrated models should also account for sociocultural considerations of indigenous stakeholders (Plagányi et al. 2013).

International Council for the Exploration of the Sea (ICES)

Europe does not have a developed climate strategy, but ICES reports trends in ecosystem state and priority pressures through Ecosystem Overviews (AORA 2017), which inform managers on a regional scale and vary by assessment region. Considered ecosystem variables are substrate, pelagic habitat, benthic communities, phytoplankton and zooplankton, cephalopods, fish, seabirds, sea mammals, non-indigenous species, and threatened and declining species and habitats. Overviews are available for the following Ecoregions: the Barents Sea (ICES 2016a), Bay of Biscay and the Iberian Coast (ICES 2016b), Celtic Seas (ICES 2016c), Greater North Sea (ICES 2016d), Icelandic Waters (ICES 2017b) and the Norwegian Sea (ICES 2017c).

Ecoregion overviews are reviewed every three years and adapted with new relevant knowledge, and are currently a mix of qualitative and quantitative approaches with a future view to increasing quantitative analysis (AORA 2017). A 2016 workshop (ICES 2016e) had identified challenges in applying ecosystem approaches, such as tools to conduct integrated trade-off analyses. European Union Working Groups (AORA 2017) have identified tools for incorporation of climate, oceanographic and ecosystem variables into resource management. Such tools could be conceptual modelling (which depicts the interrelationships between physical, biological and socio-economic approaches), risk analysis, ecosystem indicators as tools themselves (e.g. communicates human-related impacts on ecosystem), Strategic Reference Points (which include biological reference points in context of resource usage, such as conservation and socio-economic concerns), spatial planning (for reducing conflicts), traits-based models (can be used to inform inherent trade-offs between users), Models of Intermediate Complexity (MICE) (used for tactical management decisions), end-to-end models (quantitative summary of ecosystem functions) and MSEs.

South Africa

While South Africa does not directly incorporate climate or oceanographic variables into stock assessment models, a number of initiatives have been conducted which will advance South African marine management in changing environmental conditions. An initial Vulnerability to Climate Change Assessment was conducted on all of South Africa's 22 fisheries, which included marine aquaculture, following which adaptation plans were developed for three species (Hampton, Githaiga-Mwicigi et al. 2017). Further assessment of the potential impacts of climate change were made on some of the 22 stocks, see table 15.3 (Augustyn, Cockcroft et al. 2017), which noted that there already has been some impact on resources. A subsequent Climate Change Adaptation and Mitigation Plan was updated to include the Fisheries Sector (DAFF 2016), and a following workshop examined the possibility of using research as an adaptation tool for marine fisheries and aquaculture to climate change (Githaiga-Mwicigi, South African Department of Agriculture, Forestry and Fisheries, pers.comm.). The 2016 draft South Africa National Adaptation Strategy (Department of Environmental Affairs 2016) mentioned necessary trade-offs between economic production, conservation, sustainability, biodiversity and ecosystem health, which will impact production and livelihoods. Recommended adaptation strategies included using EBFM, continued environmental monitoring, supporting resiliency in small-scale fishermen, integrated coastal management and collaboration with multiple stakeholder groups. Finally a Technology Prioritization Plan has been developed, to prioritize South Africa's climate change mitigation and adaptation technologies (Githaiga-Mwicigi pers.comm.).

International Stocks

While climate variables were incorporated into some ICCAT stock assessment advice, the Science Strategic Plan (Standing Committee on Research and Statistics 2014) does not explicitly discuss use of climate variables in fisheries management for future climate conditions. It does mention filling data gaps (major uncertainties affecting advice), research needed, development of MSE frameworks for all main species that allow testing of cost / benefits of research and encouraging researchers from oceanographic, climate and socioeconomic disciplines to be appointed to specific tasks, including those on the Subcommittee on Ecosystem and Bycatch.

Summary of common elements

Of the countries and jurisdictions examined above, the common elements were: vulnerability risk assessments, reviews of research impact, a developed or developing climate strategy which considered both marine industries (fisheries and aquaculture), development of adaptation options, stakeholder engagement, management responses (e.g. EBFM) and a need for funding and capacity to support data collection, strategy development, implementation and continued resource management.

DISCUSSION

Our review was focused on evaluating the incorporation of climate, oceanographic and ecological variables in the provision of advice in the scientific peer-review and *ad hoc* processes surrounding stock assessments carried out by Fisheries and Oceans Canada. The provision of advice is generally the result of a request by operational sectors (e.g. Fishery Management) seeking information about the current and future states of renewable resources in order to determine sustainable exploitation rates. Because many fish and invertebrate stocks are short-lived with the bulk of the biomass restricted to a few age-classes, the state of each population is likely to undergo important changes on relatively short time scales. For longer-lived species with episodic recruitment, vulnerable biomass can also vary significantly among consecutive years. As a result, the advice provided is primarily tactical on time frames of 1 to 5 years although recommendations pertaining to strategic planning are also provided, for example, when population trends demonstrate persistent patterns of change that may also be linked to industry investment strategies. Globally, tactical fisheries management is still predominantly single-species oriented, with little consideration of ecosystem system processes, which ignores the fact that fish stock productivity is dependent upon the physical and biological conditions of the ecosystem (Skern-Mauritzen et al., 2016). From the perspective of vulnerability to climate change, Canada ranked as 54th out of 147 countries in a recent review (Blasiak et al., 2017), far more vulnerable than other countries reviewed here that have, or are, developing fisheries climate strategies (USA ranked 142nd, Australia ranked 133rd, European nations ranked between 79th and 147th, and South Africa ranked 130th), partly as a result of IPCC future sea surface temperature projections in northerly waters.

Stock assessments rely on reconstructing the past to understand the drivers of change in population abundance and to project into the short term future. The quality and quantity of information and knowledge available can limit our ability to evaluate the relative contribution of different factors that affect population change. However, the assessment processes have served as a foundational source of knowledge in evaluating the potential impact of climate change on future ecosystem state (Shackell et al. 2014; Hunter and Wade 2015; Stortini et al. 2015) in Canada's Oceans. Quantitative analyses or qualitative assessments based on the weight-of-evidence have served to interpret the relationships between patterns of change in population abundance and climate, oceanographic and ecological variables and served to develop projections of stock status informed by understanding of short and long-term effects of current and past environmental conditions on a species' dynamics. Our review highlighted that the peer-review process sets high requirements for the incorporation of environmental knowledge in the advisory process because uncertainty in understanding of the underlying mechanisms or pathways of effect is often cited as a limitation. There is evidence that the complex interactions among different climate, oceanographic and ecological variables can result in a shift in the relative dominance of one driver over another as a primary driver of population status as the environment and ecosystem change. Such occurrences are likely to be common and can result in the breakdown of relationships that had previously appeared reliable. For example, deviations in the relationship between projected catch rates of snow crab off the coast of Newfoundland and the extent of a climate-related thermal habitat index, based on conditions 6-8 years prior to the fishery, began to appear when groundfish stocks recovered following their collapse to historically low levels, forcing a reassessment of the elements needed in projections (DF0 2017e). The difficulties faced when incorporating climate, oceanographic and ecological variables point to the need to develop of a risk-averse approach for managing species under climate change and environmental variability. Furthermore, DFO's Ecosystem-based approach to management requires an enhanced understanding of the mechanisms that drive change rather than treating them as a source of uncertainty in stock dynamics. Nevertheless, single species assessments remain an important forecasting tool for population dynamics.

HIGHLIGHTS OF RESULTS

While 46% of the stock assessments reviewed 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 or effects of climate, oceanographic or ecological considerations. However, our results may underestimate the true consideration of climate, oceanographic and ecological variables if these variables were explored in preliminary analyses, but excluded from final reporting due to, for example, high uncertainties, and not reported in the assessment document.

Across all four questions, stock assessments of anadromous fishes, particularly salmon, consistently had a higher rate for including climate, oceanographic or ecological variables. In contrast, elasmobranchs and marine mammals typically had the lowest rates of inclusion. Salmonid population dynamics tend to be highly coupled with dominant climate and oceanographic features. However, it is notable that a large portion of assessments on Pacific salmon are not reviewed through CSAS. In contrast, elasmobranchs and marine mammals are generally managed as bycatch and subsistence fisheries, often with multi-annual assessment regimes and relatively simple assessment models. Pelagic, invertebrate and groundfish fisheries represent the bulk of commercial fisheries and included a mixture of highly productive high- and low-value fisheries.

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 requires an understanding of the biology and ecology of the target species and surrounding environmental conditions and variability. The level of relevant understanding differs considerably among stocks. Many Atlantic fish stocks have data time-series that span several decades while Arctic stocks typically have data from 10 years or less. Differences in the frequency and method of incorporating climate, oceanographic or ecological variables 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 change that affected each stock. 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. Similarly, environmental correlates of survival and migration during the freshwater phase of salmon life-histories have been extensively studied. Therefore, a large proportion of anadromous fish stock assessments incorporate these variables. 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. The Central and Arctic region included climate, oceanographic or ecological variables least frequently among the regions because most of the stocks in the region are data-limited fish stocks for which the mechanisms driving population dynamics are poorly understood. The issue around the inclusion of climate, oceanographic or ecological variables into the advisory process rests partly on our ability to detect the effect of variable(s) based on the strength of the signal and the underlying uncertainty in our estimates of state. The development and application of standards for the detection of climate, oceanographic, or ecological effects would increase the rigor and credibility of assessments that include those variables. Such analytical tools should be applied in a systematic manner as part of the stock and ecosystem assessment process(es) that include the use of climate, oceanographic, or ecological variables. This would be similar to the approach by the IPCC in the detection and attribution of climate change (Bindoff et al. 2013), and in contrast to the current *ad hoc* approach that can be affected by the vagaries of the peer-review process.

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. Habitat linkages and dependency were also included in responses to all four answers, highlighting the general importance of incorporating habitat considerations whenever possible. 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 consider environmental factors when assessing the population state or conducting projections. Many of the international stock assessments we reviewed highlighted linkages to large-scale climate drivers, such as sea surface temperature linked to North Pacific Index, ENSO or the variability in the dynamics of the California Current system.

In addition, our review identified that several Canadian assessments are not peer-reviewed through Canadian Science Advisory Secretariat. Most of the Pacific salmon assessments used in this review were documented in technical reports or bulletins only, some of which were infrequently updated (e.g., not within the last 15 years for some species). Although these documents are accessible to fisheries managers to inform management decisions, some lack the scientific rigour associated with peer-review or a description of that process. In particular, the inclusion of climate, oceanographic, and ecological variables are typically not thoroughly evaluated in those assessments.

Despite the observed differences among regions, taxa and assessment types, a clear pattern is present. 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 (e.g. Pacific salmon and Atlantic groundfish stocks). 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 as part of the Canadian advisory process 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.

Our review did not evaluate two important aspects of the inclusion of climate, oceanographic or ecological variables into the provision of advice. The first deals with whether the inferences or projections of future population state were improved by the addition of the variable(s) into the advice. While there are several examples of Canadian stock assessments that quantitatively considered COE variables in the provision of advice, there were few examples that explicitly compared results from models with COE inclusion to those without. One example, for Harp Seal, concluded that failure to consider ice-related mortality in the assessment had a significant impact on perceptions of the resource (Hammill and Stenson, 2009). For a number of years, ice related mortality of young of year Harp Seals had been included in the population model of the assessment, but the impact of its inclusion had not been tested. Hammill and Stenson (2009) examined the behaviour of the existing management framework under varying assumptions on the response of a simulated population subjected to changes in environmental, management, or model conditions. They compared the impact of including ice related mortality of young of year in a “Reference model” to population estimates and TAC advice that would be produced by an “Assessment model” that did not consider this source of mortality. In simulation testing, the Assessment model did not meet the management objective of maintaining an 80% probability that the population would remain above a precautionary threshold (Hammill and Stenson, 2009). Such an evaluation of all the assessments in this review would have required us to conduct retrospective analyses of the projections made with and without the addition of the environmental drivers over appropriate time frames relevant to the change in environmental conditions and the length of the projections. Details of the projections, or evaluation of the value of environmental information incorporated into the assessment, were often missing from the assessment documents. This would have required collection of all the data sources and assessment methods, which was well beyond the scope of this review.

The second aspect of the inclusion of climate, oceanographic or ecological variables into the provision of advice deals with whether the use of such knowledge into the provision of scientific advice was actually applied in the decision-making processes that resulted in the final allocation and exploitation of the stocks. This represents a critical perspective in any assessment of the value of scientific advice but one that is poorly documented. Although records of the scientific peer review process are generally publicly available, documentation of the subsequent elements in the decision-making process outlined at the end of the introduction is not readily available. This is a major short-coming in the need to have open, transparent and documented steps in the decision-making processes that lead to the allocation of Canadian natural resources. Without knowledge of the options (e.g. management actions) and drivers (e.g. conservation constraints versus socio-economic impacts) that led to applied management action, evaluation of the “value” of environmental considerations to future states of the fishery and ecosystem could be regarded as largely conjectural or speculative. If we are to evaluate the strength of scientific evaluations of future population states, it is essential that we piece apart the dependence on population dynamics, their responses to changes in environmental conditions and the contribution of management actions because harvests to changes in population state.

METRICS

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 in the Pacific region where the Pacific Decadal Oscillation and El Niño-Southern Oscillation capture dominant oceanographic features. One exception concerns assessments of anadromous species, which commonly considered climate metrics in all regions (e.g., Arctic Oscillation Index in the Arctic Ocean, Atlantic Multi-decadal Index in the Atlantic Ocean). Metrics describing mesoscale oceanographic features, such as upwelling, eddies, and associated currents were also considered, most commonly on assessments in the Pacific region.

Temperature, an oceanographic metric, was the most commonly used across taxonomic groups and regions. Similar findings apply to stock assessments in our global review. Temperature is amenable for inclusion in assessments, both Canadian and International, as it can be measured precisely relatively easily, is coherent across relatively broad spatial scales, and reflects general features of ocean state. For example, temperature was used not only for seasonal catchability predictions of thermal habitat (e.g. Southern Bluefin Tuna; Eveson et al., 2015), but also temperature-dependent recruitment predictions 3-4 years in the future (de Lestang et al., 2012). Ocean warming is predicted to rapidly change global marine diversity (García Molinos et al., 2015), and with it species spatial distributions. Predation was the most important ecological consideration in both quantitative and qualitative analyses, especially for groundfish, though plankton biomass and dynamics were also important in several assessments (especially pelagic, invertebrates and anadromous species). These ecological metrics are more difficult and/or costly to measure precisely, limiting their utility in many assessments. Table 3 provides a list of metrics used in recent DFO assessments. This list of metrics should be considered a starting point for stock assessment analysts and is not intended to be prescriptive.

For many assessments, the metrics listed in Table 3 were used to provide science advice, but their inclusion was often not rigorously evaluated *a priori*. For example, when they were included as covariates in assessment models, model fits were typically evaluated using correlation coefficients between modeled and observed data or information criteria (e.g., Akaike or Deviance information criteria). In a few cases more rigorous evaluations were performed using retrospective analyses and re-evaluation of statistical model fits with re-sampled data (e.g., Fraser River sockeye pre-season forecast of migration route and timing, DFO 2016a and run size, DFO 2017a). These evaluations identified the extent to which the inclusion of variables resulted in improved model fit, but did not evaluate whether the inclusion of those metrics improved scientific advice or management outcomes. In the case of Pacific sardine in the US, SST was included initially in 1998, but recruitment failures from 2006-2012 (in spite of high SST values) led to removal of SST as a harvest control rule (Zwolinski and Demer, 2014). SST related to the California current was then reapplied setting a temperature-driven harvest control rule and buffer (Hill et al., 2017), indicating that models will need to be assessed and re-assessed for validity. Even if including climatic, oceanographic or ecological metrics in assessments improves model fit, their inclusion can reduce the quality of resulting decisions if correlations among variables change over time and these changes are not accounted for. In some cases more thorough evaluations are implemented. For example, a closed-loop simulation model was used to evaluate harvest control rules accounting for time-varying productivity due to changing ocean regimes (Pestal et al. 2012). This type of model projects the status of the fish stock into the future including feedback from assessment and management actions in order to evaluate performance of various management procedures against pre-specified objectives given underlying uncertainties. These models mimic the acquisition of new data and stock assessments, application of a harvest control rules, and generation of new spawning biomass in simulated annual time steps (Kronlund et al. 2012).

Given the uncertainty in underlying mechanisms driving population dynamics, we recommend that the quantitative inclusion of climate, oceanographic and ecological metrics in assessments be rigorously evaluated and uncertainties be quantified. Similarly, periodic evaluation of the contribution, in terms of information content, of climate, oceanographic or ecological metrics to assessment forecasts should be applied to determine whether greater accuracy is achieved relative to instances when they are excluded. Frequent re-evaluation of hypotheses and metrics is warranted given possible changes in correlations among variables over time, especially under climate change. In addition, in our review we found that numerous assessments included climatic, oceanographic, and ecological metrics quantitatively in assessments, but failed to describe the underlying mechanisms linking those metrics to population dynamics (e.g., Bay of Biscay anchovy). We further recommend that mechanisms (hypothetical and/or empirically tested) be described in assessments to inform analysts of conditions under which relationships might break down or change over time (i.e., when assumptions are not met).

Table 3. Climate, oceanographic, and ecological metrics considered in DFO stock assessments.

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

APPROACHES

DFO stock assessments that quantitatively included climate, oceanographic or ecological variables in providing advice applied a range of approaches, from simple univariate statistical approaches (e.g. correlation analysis or linear regression analysis), to multivariate statistical analyses (e.g. multiple linear regression, generalized additive models, principal components analysis) and model parameter estimation, most notably for natural mortality, growth or catchability. There were some examples of applying climate, oceanographic or ecological variables to revise biological benchmarks for characterizing stock status or as sensitivity analyses to evaluate or revise harvest strategies.

It is somewhat surprising, given the large amount of published literature linking climate and environmental drivers to fish population dynamics (see Lindegren and Brander, 2018 for a recent compilation), that few examples exist globally where indices of those drivers are included, either quantitatively or qualitatively, in stock assessments. However, the value of climate, oceanographic or ecological considerations into short-term tactical forecasts (1-2 years) may be of limited value unless stock status is highly responsive to year-to-year variations in environmental conditions. Moderate-term strategic projections, when possible, may be more strongly affected if changes in population state are linked to climate, oceanographic or ecological covariates. Population responses are likely to be linked to the strength and rapidity of environmental change(s) experienced, and extreme events may further influence population productivity.

Skern-Mauritzen et al. (2016) suggested only about 2% of stock assessments worldwide include information on climate or environmental drivers in tactical management decisions. However, Skern-Mauritzen et al. (2016) did not include a search of DFO stock assessments and our review indicates that DFO is well above this reported proportion, with a considerably greater proportion of the stock assessments that we reviewed having incorporated climate, oceanographic or ecological variables either quantitatively (21%) or qualitatively (31%) and providing advice (27%) based on that inclusion.

In our review of global stock assessments, we identified several case studies that included climate, oceanographic or environmental variables in final advice to management produced by the US National Marine Fisheries Service (NMFS). To our knowledge, NMFS is also the only jurisdiction with a developed and implemented national strategy for incorporating climate science into fisheries science (Link et al., 2015). Stock assessment attributes addressed by both DFO and NMFS with quantitative inclusion of climate, oceanographic or ecological information are similar (i.e. natural mortality, CPUE standardization, growth, recruitment, productivity and harvest strategies), but DFO has more of a focus on natural mortality parameter estimation (e.g. time-varying within the model) and NMFS has more of a focus on CPUE standardization (e.g. time-varying catchability). These types of stock assessments are mainly statistical catch-at-age models or virtual population analyses which are limited to data-rich stocks (i.e. long time-series with reliable estimates of catch, effort, fishery-independent indices, age, length and maturity).

Another difference to note between DFO and NMFS stock assessments that quantitatively included climate, oceanographic or ecological information is that all the NMFS stock assessments we reviewed provided hypotheses or outlined mechanisms explicitly linking those drivers to population dynamics but our review was not an exhaustive assessment of the NMFS assessments. Within DFO stock assessments, this was not always the case. Often, climate, oceanographic or ecological variables were quantitatively included without sufficient rationale. It should also be noted that DFO stock assessments often simply referred to unspecified environmental impacts on productivity, growth or mortality. These two observations may indicate a lack of DFO process-oriented research that helps assessment analysts to identify empirical support for hypotheses or conceptual mechanisms. Given that simple correlations between proxy environmental indices and population dynamics will change over time (Myers 1998), the inclusion of climate, oceanographic or ecological drivers without a good understanding of ecosystem process will likely lead to model failure or may be viewed by managers as unreliable. This may account for the low proportion of DFO stock assessments that quantitatively included climate, oceanographic or ecological information and did in fact provide advice based on that inclusion. It also speaks to the need to carefully monitor departures from empirical relationships to determine when and why they may break down. This is similar to the US where we found several NMFS assessments in which there were conceptual models about the effect of climate, oceanographic and ecological variables (e.g., Gulf of Alaska walleye Pollock prey-predator effects (Dorn, Aydin et al. 2017); temperature effects on American lobster (ASMFC American Lobster Stock Assessment Review Panel 2015); oceanographic conditions on North and South Black Sea Bass stocks (Northeast Fisheries Science Centre 2017a) and scup (ASMFC Scup Working Group 2015)) but which were unable to find sufficiently strong relationships to warrant incorporation of their effects into the advice.

The qualitative approaches applied in DFO stock assessments were mainly for interpretation of trends or anomalies in stock indices such as CPUE or distribution. The small proportion that did qualitatively use climate, oceanographic or ecological metrics to forecast stock dynamics did so by applying a multiple indicator diagnostic approach (i.e. the Traffic Light Approach) to either provide rationale for selecting a model's mortality scenario (DFO 2017b) or for assessing stock status relative to reference points and provide an outlook for future biomass (DFO 2017c). In a recent global assessment review, the direct inclusion of ecosystem drivers was rare, but contextual assessments of ecosystem indicators were offered more frequently and had influenced tactical decision making, although often stated explicitly in assessment reports (Skern-Maurtizen et al., 2016), as we also found. The Okanagan sockeye salmon stock assessment (DFO 2017b) in fact did not develop its own suite of indicators, but rather it applied an existing NMFS ecosystem report card for Coho and Chinook salmon in the California Current (Peterson et al., 2017). Overall, the qualitative approaches in DFO stock assessment to including climate, oceanographic or ecological information are not as complex or developed as the approach broadly applied in NMFS. For several Large Marine Ecosystems, NMFS produces complex Ecosystem Status Reports with comprehensive indicators across all aspects of the ecosystem (see for example Zador and Yasumiishi 2017). As noted, these Ecosystem Status Reports go beyond simple interpretation of trends or anomalies in stock indices to providing context for informed decision-making by resource managers. However, what is less clear is how they currently inform the stock assessment process *per se*. DFO is currently standardizing the State of the Ocean reporting which, if further developed, could offer the opportunity to address gaps in DFO's research into meaningful ecosystem indicators and their application to provision of science advice and therefore could be used in stock assessment considerations. DFO vulnerability assessments for the Pacific (DFO, 2013c), Atlantic (DFO, 2013d; Stortini et al. 2015) and Arctic (DFO, 2013c) could also be summarized and used for informed decision-making science processes. Climate vulnerability rankings have been developed for some species at the species level (Stortini et al. 2015; Hare et al., 2016). In the US, rankings were directly applied to fisheries management as a function of biological sensitivity and climate exposure in the US (Gaichas et al., 2017). Composite indexes of Ecosystem Status reports can be used to develop a regional index and can serve to integrate climate, physical and ecological indicators in science advice (Northeast Fisheries Science Centre, 2017b). Development of comprehensive Ecosystem Status Reports represents a critical step in the incorporation of climate, oceanographic and ecological considerations in stock assessments.

DFO stock assessments that quantitatively or qualitatively applied climate, oceanographic or ecological variables provided tactical advice expected to be valid for a time-scale of 1-5 years. This is the result of the management needs for advice in the short-term (i.e. a continued reliance on single-species stock assessment), and perhaps reflects the increased uncertainty in forecasted climate, oceanographic or ecological variables on decadal to longer time-scales (if those forecasts are even available). Development of strategic advice (e.g. harvest strategies) based on Management Strategy Evaluations (MSE) could include ranges of uncertainty related to climate change and environmental variability and provide alternative harvest strategies that are robust to those ranges of uncertainty (Lindegren and Brander, 2018) and provide management options for longer time-scales (5 years to decadal). The Australian Fisheries

Management Authority (AFMA) has developed Adaptive Management in Australian Fisheries management plans, where MSEs are used to conduct an evaluation of the entire management cycle in developing harvest strategies (Ogier et al., 2016). A good example would be the MSE noted above for a northern Australian sea cucumber *Holothuria scabra* (Plagányi et al. 2012) which applied a mid-high range IPCC scenario for 2030 projections to test alternative harvest strategies under climate change. The only closed-loop simulation MSEs within DFO have been applied to Sablefish in Pacific region (Cox et al. 2011, DFO 2017d) and Pollock in Maritimes region (DFO 2011, DFO 2015), although neither considered climate change or environmental variability in the operating models or scenarios. Two advantages of the MSE approach are that uncertainty in the relationship between population dynamics and climate, oceanographic, and ecological variables can be explicitly accounted for, and different hypotheses about the pathways of effects can be evaluated.

While we have tried to capture broadly the generalities in the qualitative and quantitative approaches applied within DFO stock assessments, Skern-Mauritzen et al. (2016) made a salient observation that is pertinent to our discussion on how to include climate and environmental drivers in stock assessment advice: the scientific process to do so is driven by individuals, or teams, that adapt their approaches to their unique case of data availability and the understanding of processes involved. Uncertainties in climate model projections may also contribute to policy-makers' lack of confidence, especially when moving from tactical to strategic decision-making (Burden et al., 2017), and therefore integration of climatologists and fisheries scientists would be beneficial. Additionally, Skern-Mauritzen et al. (2016) observed that regional agencies with long-standing programs in monitoring the environment and fish stocks (notably NMFS and northern ICES countries), have also supported many studies on ecosystem drivers of fish productivity, and are the same agencies that are at the forefront of implementing inclusion of ecosystem processes in tactical fisheries management. This highlights the priority that should be given to maintaining and improving the scientific support within DFO for ecosystem-based research, particularly the process-oriented research that postulates conceptual mechanisms, and provides the empirical-basis for linking climate and environmental drivers to fish stock productivity. Simulation testing and sensitivity analyses in assessments could test the assessment assumptions along with conceptual mechanisms within a MSE framework. Doing so would help define the main ecosystem drivers, the ecosystem monitoring support required and identify how to modify stock assessment models to incorporate those drivers.

MOVING FORWARD

A recent global analysis of the likely impacts of climate change on fisheries concluded that effective adaptive management responses could result in more prosperous fisheries, whereas maladaptive responses (e.g., status quo) were projected to lead to considerable losses in biomass, harvests and profitability (Gaines et al. 2018). This result underscores the need to move forward with the incorporation of climate change into science advice for fisheries management by DFO. It is currently occurring to varying degrees within Canada (and across the globe), using a range of approaches and tools. Fundamentally, the foregoing review highlights that understanding the various ways in which climate change may affect commercial species also requires understanding of the effects of climate change throughout the ecosystem (i.e., the consideration of climate change is one particular aspect of ecosystem-based fisheries management and cannot be treated separately). Climate change can affect species directly, indirectly or both. With respect to commercial species or access to stocks, the greatest risk to productivity from climate change may not be direct, but may rather be transmitted through the food web by, for example, changes in prey productivity, changing distributions or species compositions, or increase in predators.

There are several key take home messages from this review that can form the basis for a DFO plan for moving forward:

1. **Climate Change is an integral element of EBFM**: Climate, oceanographic and ecological factors are all linked and should be considered jointly. Climate change is one aspect of EBFM. Where climate models are required, focusing on major modes of ocean variability (e.g. ENSO, North Atlantic sub-polar gyre) and their biological consequences may be more feasible to integrate initially. Sea surface temperature predictions would be useful as often historical datasets are often decades long and forecasting skills using hindcasts over a 50 year time scale can increase prediction skills over 1-10 year scales (Tommasi et al., 2017).
2. A combination of **qualitative and quantitative** approaches is required, moving towards quantitative approaches where data are available. Qualitative approaches can provide broader ecosystem context, the development of hypotheses and may enable the provision of advice in data poor situations. Quantitative approaches are used to explore relationships between climate, oceanographic or ecological variables and stocks. Where appropriate they can then be used to develop Harvest Control Rules and reference points, or provided the basis for MSEs. There are several cases in this review in which some stock assessments make use of either or both of these approaches (e.g. DFO 2016a Run timing and diversion rate models for Fraser River Sockeye; DFO 2016b Stock assessment of northern cod; DFO 2017c Assessment of northern shrimp on the Eastern Scotian Shelf), but for other stocks of the same species the approach(es) is (are) not applied because uncertainty in the strength of the relationship and/or signal. Such cases should form the basis for further development or evaluation of the benefits of expanding the application of climate, oceanographic or ecological knowledge in the advisory process.
3. **Ecosystem assessments** (i.e. status reports) can, and should, inform fish stock assessments. They provide a means to track change in ecosystem properties that may affect the stock of interest. They also provide the potential to track coherent trends across stocks and or ecosystem properties that may indicate broader change and can provide early warning signals of change and provide an overall assessment of the status of the ecosystem. Most regions of DFO already use indicators to assess ecosystem status, which have contributed to State of the Oceans reports. Ecosystem assessments can improve operational efficiencies since the resulting data support multiple goals, including stock assessment, habitat monitoring, biodiversity monitoring, COSEWIC/SARA assessments and aquatic invasive species detection. Priority for State of the Ocean reports should be the application of an indicator selection process, rather than *ad hoc* inclusion of time-series.
4. **Distributional change** is considered in only a few DFO stock assessments (and mainly for invertebrates), yet there is ample evidence to indicate that there will be a northwards shift for many species as a result of increasing temperatures (e.g., Shackell et al. 2014; Kleisner et al. 2017). Range shifts may also bring new opportunities for fisheries adaptation to access new commercial species. Furthermore, **changes in phenology** of the stock (e.g. migration, spawning) and their environment as a result of climate change are also likely to play important roles in population dynamics through their effects on growth, recruitment/survival, etc.

5. There is great value in the use of **multi-model, or model ensemble approaches**, whereby a single species stock assessment model can be nested within models that capture a greater part of the ecosystem (e.g., minimally realistic models, MICE models, ecosystem models) and take account of trophic interactions and other indirect effects. Further, ensemble, or model averaging approaches can also provide more robust estimates (Anderson et al. 2017, Rosenberg et al. 2018). Currently, DFO's stock assessments are generally conducted on a species by species basis with no linkage or nesting to larger ecosystem models or to broader ecosystem understanding.
6. There are inevitable **trade-offs** between the state of our knowledge (and its level of **uncertainty**) and the necessity for precaution in management. As uncertainty increases, so must precaution. There are examples of harvest control rules that include buffers (e.g., the Pacific Sardine has harvest control rule with a temperature-driven uncertainty buffer see above (Hill et al. 2017)). Fishing reference points will need to be re-evaluated or re-estimated as environmental change may alter species productivity or predator fishing may alter prey responses (Kumar et al., 2017). Assessments of trade-offs in fisheries and economic models have been performed (Essington et al., 2017) and should not overlook the human component of ecosystem management.
7. **Management Strategy Evaluation** (MSE) plays a key role in developing robust management approaches for climate change in several international jurisdictions. This has not yet been applied in a climate change context in Canada. This would require understanding of the mechanisms underlying stock dynamics, appropriately downscaled climate projections based on a range of management and climate change scenarios (Punt et al., 2014). However, a full understanding is not essential - Hypotheses and uncertainties can be evaluated with varying degrees of detail, and additional understanding can be built in as it becomes available.
8. Understanding the likely impacts of climate change requires systematic **process oriented research and capacity.** There is an ongoing requirement for comprehensive research on factors that affect the distribution and abundance of fish and prey species, trophic structure, predator-prey dynamics, and species interdependencies.
9. **Social and Economic impacts of climate change –** there was no explicit consideration of the social and economic impacts of climate change in the DFO stock assessments reviewed. However, both are widely recognised as integral to EBFM (Essington et al. 2017 and references therein, AORA 2017) and to managing for climate change (Link et al., 2015, DAFF 2016, Pinsky and Fogarty 2013, Allison et al. 2015). Climate change will impact anthropogenic activities such as fishing that depend on commercial species for their livelihoods and to generate business profits. Shifting species distributions may lead to conflict over quota. Some species will benefit from climate change – how will these benefits be distributed among fisheries? Managing for climate change requires consideration of the social and economic consequences of climate change on commercial species productivity, behaviour and distribution. Social and economic analyses of climate change are a critical gap.

Despite advancing an ecosystem approach in the Sustainable Fisheries Framework , and the stipulation in the Prime Minister's Mandate letter to the Fisheries Minister to "Use scientific evidence and the precautionary principle, and take into account climate change, when making decisions affecting fish stocks and ecosystem management", DFO is faced with several challenges if it is to develop a nationally coherent, ecosystem-based responsible approach to managing for climate change:

1. Stock assessments need to be integrated with ecology, oceanography, climatology, sociology and economics and put into the broader ecosystem and socio-economic context to support resilient and flexible management approaches.
2. There is currently a lack of capacity and expertise to integrate and adopt this strategy.

To make the process more inclusive, (J. Link and P. Lynch, NMFS, US, personal communication) suggested two approaches that may serve to prioritize implementation of an ecosystem approach to stock assessments:

1. Develop a decision tree to prioritize stocks for incorporation of climate, oceanographic or ecological variables in the assessment.
2. Provide a forum for expert groups to come together to identify which stocks would most likely benefit from climate, oceanographic or ecological information in the development of advice. This could be carried out regionally to address local needs before a national program is fully implemented.

Based on our review, we propose three approaches for incorporating climate change considerations into Science advice for fisheries management that encapsulate the range of possibilities:

Status Quo - Develop National Approach using current resources

- Develop tool box of existing methods and tools
- Transfer knowledge across stocks, regions and assessment scientists
- Include conceptual understanding of climate, oceanographic, ecological factors affecting stock of interest in background sections of stock assessment documents
- Develop integrated ecosystem assessments for all regions based on established indicator selection process that integrate across disciplines (biological, chemical and physical oceanography; population and community status, trends and structure, etc.)
- Include climate change or environmental variability in the operating models or scenarios of existing and developing DFO Management Strategy Evaluations

Interim EBFM Approach - Develop National Approach using additional resources

- Elements from Status quo, plus:
- Build on existing expertise to develop more quantitative approaches
- Increase capacity dealing with Climate Change and Ecosystem Research and provide increased support for fisheries stock assessments
- Apply multiple modelling and empirical approaches to develop a comprehensive understanding of climate, oceanographic and ecosystem drivers affecting stock dynamics
- Hold National Training Workshops to develop expertise in Ecosystem-based Fisheries Management, including qualitative approaches for stock assessments
- Develop additional expertise in Management Strategy Evaluation, including consideration of harvester responses to changes in environmental conditions and management practices.

Integrated EBFM Approach

- Elements from previous two sections, plus:

- Develop a National Fisheries Climate Science Strategy
- Develop Regional Action Plans aimed at better understanding how climate impacts living marine resources (LMRs), and determine how to reduce impacts and how to increase resilience of LMRs and LMR-dependent communities.
- Develop understanding from the stock to the ecosystem, using multiple modelling and empirical approaches
- Provide regular assessments of ecosystem and socio-economic status indicators
- Develop capacity in social sciences and economics to include human dimensions research into the impact of climate changes
- Promote an interdisciplinary team approach for stock assessments, with inclusion of oceanographers, ecologists, social scientists and economists (e.g. Link et al. 2015; Figure 13).

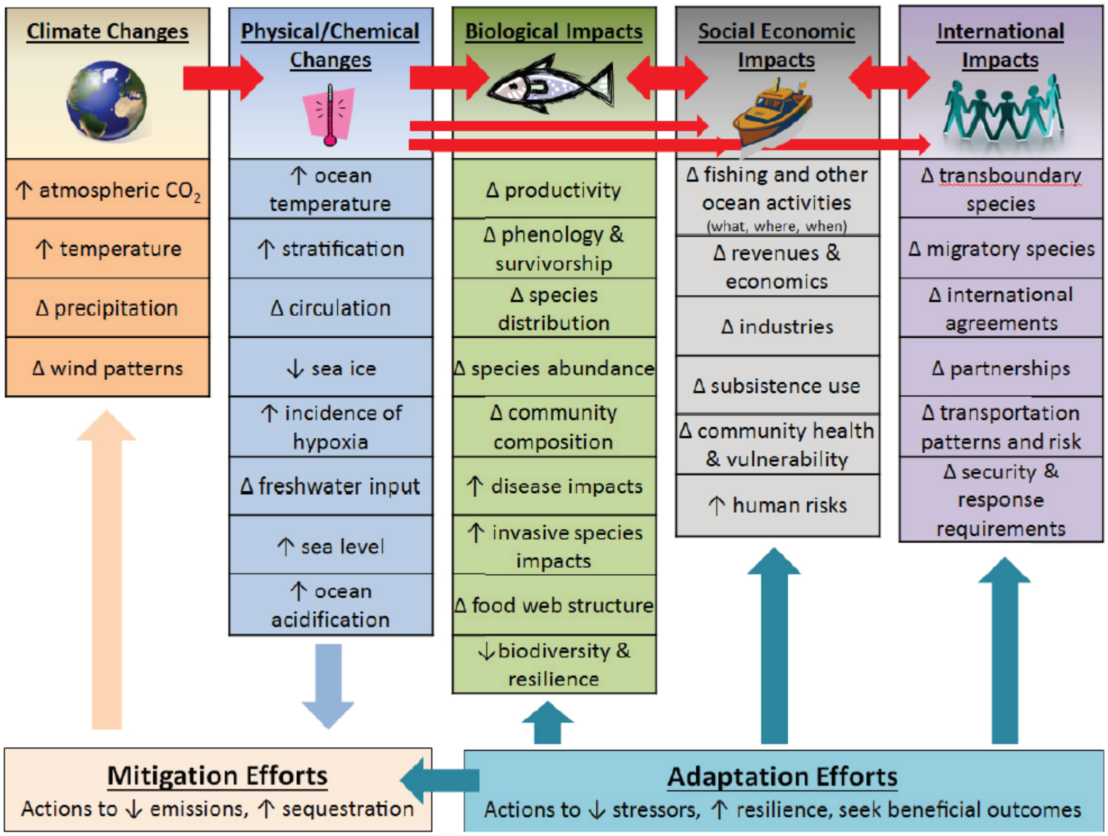

Figure13. Schematic diagram illustrating current and/or projected impacts of climate change on major components of marine and coastal ecosystems. From Link et al. (2015; NOAA Fisheries Climate Science Strategy).

RECOMMENDATIONS

Most immediately, we recommend that DFO:

1. Develop and implement a plan for an Ecosystem-Based Fisheries Management (EBFM) Approach that is linked to the development of a National Fisheries Climate Science Strategy, which aims to include consideration of social and economic impacts of climate change – Action: Create National and Regional cross-Sectoral Working Group (Science, Fishery Management, Oceans, Policy) to develop an Action Plan and implementation strategy to move toward EBFM in decision-making.
2. Renew Commitment to Foundational Research for EBFM: Climate Change is an integral element of EBFM because climate, oceanographic and ecological factors are all linked and should be considered jointly. Our review of the stock assessment process by Fisheries and Oceans Canada highlighted inconsistencies in the environmental information content of advisory documents, which may have often been a reflection of the state of knowledge surrounding a stock. The predominance of a lack of understanding of underlying relationship(s) between stock dynamics with climate, oceanographic and ecological variables as the reason for the exclusion of environmental considerations in the provision of advice highlights weaknesses in DFO's Science activities over many years. Basic research is a foundational element for the development of an ecosystem-based framework for management. Understanding mechanisms that drive change can only be achieved through directed and repeated efforts to study the underlying processes in a broad range of conditions using statistical and modelling approaches. International research programs have demonstrated the value of fundamental research in the evaluation of the drivers of change in stock and ecosystem dynamics. Development of a strategic approach to achieving ecosystem sustainability, while relying on tactical advice for short-term action plans, will only be achieved when the impact of human activities (e.g. exploitation) can be framed relative to the underlying variability in the environment and the ecosystem – Action: Develop coordinated funding strategy for Core and Sectoral Research activities.
3. Conduct Response (formerly Vulnerability) Assessment to evaluate which stocks are highly responsive to climate change (either negatively or positively):
    - Focus research on mechanism of environmental forcing of stock dynamics
    - If a quantitative population model exists, assess whether inclusion/estimation time-varying variables/parameters is possible and/or informative
    - Determine potential consequences to forecast of population trends
    - Develop spatial indices that can characterize distributional shifts
    - Assess whether changes in phenology are detectable and evaluate their potential consequences to productivity and to timing of fishing season
    - Identify potential climate impacts on prey and predator productivity and distribution

        Action – Reprise ACCASP basin scale Working Groups to update critical elements reviews of Climate Trends and Projections and Impacts, Vulnerabilities and Opportunities pertinent to Response Assessment
4. Revise the format of DFO Science Advisory Reports (or similar documents) to require a section on Ecosystem, Environment (e.g., physical, chemical and biological oceanographic status) and Climate Change Considerations that would:
    - Provide summary of “Response Assessment”
    - Summarize knowledge (or lack thereof) of mechanisms that underlie the relationships between species with climate, oceanographic and ecological variables;

  - Describe changes/trends in key ecosystem components (e.g. prey, community structure, predators) based on ecosystem assessments;
  - Identify thermal ranges/ distribution shift knowledge;
  - Identify gaps in knowledge;
  - Include a mandatory bullet in Advisory Summary to highlight knowledge and uncertainty of linkage with environmental and ecosystem drivers;
  - Include consideration of likely climate impacts on the fishery.

   Furthermore, we recommend that for stock assessments that include climate, oceanographic, and/or ecological variables in provision advice, that alternative advice that did not consider those variables also be documented. This would add transparency in decision making and allow analysts to retrospectively re-evaluate decisions (or forecasts) in subsequent years. The source of information for Ecosystem, Environment and Climate Change Considerations should themselves be developed through a peer-review process or forum.

5. Work toward the broader and more environmentally comprehensive application of Management Strategy Evaluation approaches in assessments of key fish stocks. Simulation testing and sensitivity analyses in assessments could evaluate assumptions associated with conceptual mechanisms within a MSE framework. Doing so could help define ecosystem drivers, ecosystem monitoring support required and identify how to modify stock assessment models to incorporate those drivers. Given the uncertainty in underlying mechanisms driving population dynamics, we recommend that the quantitative inclusion of environmental metrics in assessments be rigorously evaluated and uncertainties be evaluated and peer-reviewed. Frequent re-consideration of hypotheses and metrics is warranted given possible changes in the correlations among variables over time and the potential change in the balance of drivers under climate change. Action – develop capacity for MSE. Specifics will be dependent on progress in items 1-4.
6. Aim to develop a stronger link between Science, Economics and Policy Sectors of DFO to plan the development and acquisition of social science expertise needed to evaluate the socio-economic consequences and impacts of climate change and to evaluate trade-offs in management actions using an MSE approach (e.g. Holsman et al. 2017). Action: Requires Departmental-level coordination of cross-Sectoral action plan.
7. DFO should collaborate and coordinate with other countries, such as the U.S. that have national policies for EBFM and climate science. There are likely lessons to be learned in both directions of this collaboration. Additionally, from the U.S., a draft plan has been developed that provides guidance and a detailed approach to determining when and how stock assessments should be expanded to include ecosystem factors. It may be fruitful for collaboration on testing and implementing this process. Action – formation of a national DFO/NMFS ecosystem working group.

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REFERENCES CITED

Allain, G., P. Petitgas and Lazure P. 2001. The influence of mesoscale ocean processes on anchovy (*Engraulis encrasicolus*) recruitment in the Bay of Biscay estimated with a three-dimensional hydrodynamic mode. Fisheries Oceanography 10: 151-163.

Allison, E.H. and Bassett, H.R. 2015. Climate change in the oceans: Human impacts and responses. Science 350: 778-782.

Andersen K.H., and Brander K. 2009. Expected rate of fisheries-induced evolution is slow. Proceedings of the National Academy of Sciences of the United States of America 106: 11657-11660.

Anderson, S.C., Cooper, A.B., Jensen, O.P., Minto, C., Thorson, J.T., Walsh, J.C., Afflerbach, J., Dickey-Collas, M., Kleisner, K.M., Longo, C. and Osio, G.C. 2017. Improving estimates of population status and trend with super-ensemble models. Fish and Fisheries, 18: 732-741.

AORA (2017). Working Group on the Ecosystem Approach to Ocean Health and Stressors. January 2017, Reykjavik, Iceland: 53p.

ASMFC American Lobster Stock Assessment Review Panel (2015). American Lobster Stock Assessment Peer Review Report 2015, Atlantic States Marine Fisheries Commission, NOAA: 493p.

ASMFC Scup Working Group (2015). 60th SAW Assessment Report for Scup, Atlantic States Marine Fisheries Commission: 13-334.

Augustyn, J., A. Cockcroft, S. Kerwath, S. Lamberth, J. Githaiga-Mwicigi, G. Pitcher, M. Roberts, C. D. van der Lingen and L. Auerswald 2017. South Africa. In: Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis. B.F. Philips (Ed.), Wiley-Blackwell, pages 479-522.

Bindoff, N.L., Stott, P.A., AchutaRao, K.M., Allen, M.R., Gillett, N., Gutzler, D., Hansingo, K., Hegerl, G., Hu, Y., Jain, S., Mokhov, I.I., Overland, J., Perlwitz, J., Sebbari, R. and Zhang, X. 2013. Detection and Attribution of Climate Change: from Global to Regional. *In:* Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Edited by Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. and Midgley, P.M. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. Chapter 10, pages 867-952.

Blasiak, R., Spijkers, J., Tokunaga, K., Pittman, J., Yagi, N. and Osterblom, N. 2017. Climate change and marine fisheries: Least developed countries top global index of vulnerability. PLoS One 12(6): e0179632. https://doi.org/10.1371/journal.pone.0179632.

Boldt, J. 2008. Ecosystem Considerations for 2008. Alaska Fisheries Sciences Centre, 7600 Sand Point Way NE, Seattle, WA 98115: 261p.

Borja, A., Uriarte, A. S., Egaña, J., Motos, L. and Valencia, V. 1998. Relationships between anchovy (*Engraulis encrasicolus*) recruitment and environment in the Bay of Biscay (1967–1996). Fisheries Oceanography 7: 375-380.

Borja, A., Uriarte, A., Valencia, V., Motos, L. and Uriarte, A. 1996. Relationship between anchovy (*Engraulis encrasicolus* L.) recruitment and the environment in the Bay of Biscay. Scientia Marina 60(Suppl. 2): 179-192.

Burden, M., Kleisner, K., Landman, J., Priddle, E. and Ryan, K. E. 2017. Workshop report: Climate-related impacts on fisheries management and governance in the North East Atlantic: 38p.

Commission for the Conservation of the Southern Bluefin Tuna 2016. Assessment of the Southern Bluefin Tuna Fishery December 2016, Commonwealth of Australia: 27p.

Commission for the Conservation of the Southern Bluefin Tuna 2017. Report of the Twenty Fourth Meeting of the Scientific Committee. 2 September, Yogyakarta, Indonesia: 124p.

Cox, S., Kronlund, A.R. and Lacko, L. 2011. Management procedures for the multi-gear sablefish (*Anoplopoma fimbria*) fishery in British Columbia, DFO Canadian Science Advisory Secretariat Research Document 2011/063. viii + 45 p.

CISRO, 2018. Australian fisheries stocks under climate change. Non-technical summary, 8p.

DAFF 2016. Climate Change Adaptation and Mitigation Plan for South African Agriculture, Forestry, and Fisheries. Pretoria, South Africa, Department of Agriculture, Forestry and Fisheries: 90p.

de Lestang, S., Caputi, N., How, J., Melville-Smith, R., Thomson, A. and Stephenson, P. 2012. Stock Assessment for the West Coast Rock Lobster Fishery, Department of Fisheries, Western Australia: 200p.

Department of Environmental Affairs 2016. South Africa National Adaptation Strategy (draft), Department of Environmental Affairs, Republic of South Africa: 122p.

DFO. 2011. Western Component (4Xopqrs5) Pollock Management Strategy Evaluation. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2011/054.

DFO. 2013a. 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. 2013b. 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. 2013c. 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.

DFO. 2013d. 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. 2015. Western Component (4Xopqrs5) Pollock Harvest Control Rule Update Report. DFO Can. Sci. Advis. Sec. Sci. Resp. 2015/003.

DFO. 2016a. Run Timing and Diversion Rate Models for Fraser River Sockeye. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2016/008.

DFO. 2016b. Stock Assessment of Northern Cod (NAFO Divs. 2J3KL) in 2016. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2016/026.

DFO. 2017a. Pre-season run size forecasts for Fraser River Sockeye (*Oncorhynchus nerka*) and Pink (*O. gorbuscha*) salmon in 2017. DFO Can. Sci. Advis. Sec. Sci. Resp. 2017/016.

DFO 2017b. 2018 Salmon Outlook, Dec. 2017.

DFO. 2017c. Assessment of Northern Shrimp on the Eastern Scotian Shelf (SFAs 13-15). DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2017/005.

DFO. 2017d. Evaluating the robustness of management procedures for the Sablefish (*Anoplopoma fimbria*) fishery in British Columbia, Canada for 2017-18. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2017/017.

DFO. 2017e. Assessment of Newfoundland and Labrador (divisions 2HJ3KLNOP4R) Snow Crab. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2017/023.

Dorn, M., Aydin, K., Fissel, B., Jones, D., McCarthy, A., Palsson, W. and Spalinger, K. 2017. Chapter 1: Assessment of the Walleye Pollock Stock in the Gulf of Alaska. NPFMC Gulf of Alaska SAFE, North Pacific Fishery Management Council, pages 47-182.

Duplisea, DE, Roux, M-J, Hunter, KL, and Rice, J. 2020. Resource management under climate change: a risk-based strategy to develop climate-informed science advice. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/044. v + 45 p.

Ecosystem Assessment Program 2012. Ecosystem Status Report for the Northeast Shelf Large Marine Ecosystem - 2011. National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026: 32p.

Edeline E., Carlson, S.M., Stige, L.C., Winfield, I.J., Fletcher ,J.M., Ben, James J., Haugen, T.O., Vollestad, L.A., and Stenseth, N.C. 2007. Trait changes in a harvested population are driven by a dynamic tug-of-war between natural and harvest selection. Proceedings of the National Academy of Sciences of the United States of America 104:15799-15804.

Edwards, A.M., Haigh, R., Tallman, R., Swain, D.P., Carruthers, T.R., Cleary, J.S., Stenson, G. and. Doniol-Valcroze, G..2017. Proceedings of the Technical Expertise in Stock Assessment (TESA) National Workshop on 'Incorporating an ecosystem approach into single-species stock assessments' 21-25 November 2016, Nanaimo, British Columbia. Canadian Technical Report of Fisheries and Aquatic Sciences. 3213. vi+53p.

Essington, T.E., Ciannelli, L., Heppell, S.S., Levin, P.S., McClanahan, T.R., Micheli, F., Plagányi, E.E., van Putten, I.E. 2017. Empiricism and Modeling for Marine Fisheries: Advancing an Interdisciplinary Science. Ecosystems 20: 237-244.

Eveson, J. P., Hobday, A. J., Hartog, J. R., Spillman, C. M. and Rough, K. M. 2015. Seasonal forecasting of tuna habitat in the Great Australian Bight. Fisheries Research 170: 39-49.

Gaichas, S., DePiper, G., Seagraves, R., Colburn, L., Loftus, A., Sabo, M. and Muffley, B. 2017. DRAFT Mid-Atlantic EAFM Risk Assessment Documentation and Results, Mid-Atlantic Fisheries Management Council**:** 34p.

Garcia, S.M., Kolding, J., Rice, J., Rochet, M.J., Zhou, S., Arimoto, T., Beyer, J.E., Borges, L., Bundy, A., Dunn, D., Fulton, E.A., Hall, M., Heino, M., Law, R., Makino, M., Rijnsdorp, A.D., Simard, F., and Smith, A.D.M. 2012. Reconsidering the consequences of selective fisheries. Science 335:1045-1047.

García Molinos, J., Halpern, B.S., Schoeman, D.S. Brown, C.J., Kiessling, W., Moore, P.J., Pandolfi, J.M., Poloczanska, E.S., Richardson, A.J. and Burrows M.T. 2015. Climate velocity and the future global redistribution of marine biodiversity. Nature Climate Change 6: 83-88.

Gattuso, J.-P., Magnan, A., Bille, R., Cheung, W.W.L., Howes, E.L., Joos, F., Allemand, D., Bopp, L., Cooley, S.R., Eakin, C.M., Hoegh-Guldberg, O., Kelly, R.P., Portner, H.-O., Rogers, a. D., Baxter, J.M., Laffoley, D., Osborn, D., Rankovic, A., Rochette, J., Sumaila, U.R., Treyer, S. and Turley, C. 2015. Contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios. Science, 349(6243):

Githaiga-Mwicigi, J. (South African Department of Agriculture, Forestry and Fisheries, personal communication). Email: South African stock assessments using climate indices. H. Gurney-Smith: 3p.

Hammill, M. O. and Stenson, G. B. 2010. A preliminary evaluation of the performance of the Canadian management approach for harp seals using simulation studies. DFO Can. Sci. Advis. Sec. Res. Doc. 2009/093. iv + 47 p.

Hampton, I., Githaiga-Mwicigi, J., Lamberth, S. J., Pitcher, G. C., Pretorius, M., Samodien, F., Van der Lingen, C. and Yemane, D. 2017. Report on the DAFF Workshop on Fisheries Vulnerability to Climate Change. 2-3 September 2015, Foretrust House, Cape Town: 39 p.

Hanke, A. R. 2017. On developing an Ecosystem Report card for ICCAT.

Hare, J. A., Morrison, W. E., Nelson, M. W., Stachura, M. M., Teeters, E. J., Griffis, R. B., Alexander, M. A., Scott, J. D., Alade, L., Bell, R. J., Chute, A. S., Curti, K. L., Curtis, T. H., Kircheis D., Kocik, J. F., Lucey, S. M., McCandless, C. T., Milke, L. M., Richardson, D. E., Robillard, E., Walsh, H. J., McManus, M. C., Marancik, K. E. and Griswold, C. A. 2016. A Vulnerability Assessment of Fish and Invertebrates to Climate Change on the Northeast U.S. Continental Shelf. PLOS ONE 11(2): e0146756

Herring, S.C., Christidis, N., Hoell, A., Kossin, J.P., Schreck III, C.J. and Stott, P.A. 2018. Explaining Extreme Events of 2016 from a Climate Perspective. Bulletin of the American Meteorological Society, 99: S1–S157.

Hilborn R. 2016. Correlation and Causation in Fisheries and Watershed Management. Fisheries 41:18-25.

Hill, K. T., Crone, P. R. and Zwolinski, J. P. 2017. Assessment of the Pacific sardine resource in 2017 for U.S. management in 2017-2018. Briefing Book, Agenda Item G.5.a. Portland, Oregon, Pacific Fishery Management Council: 146p.

Hobday, A. J. 2018. Email correspondence: climate strategy. H. Gurney-Smith: 3p.

Hobday, A. J., Hartog, J. R., Spillman, C. M. and Alves, O. 2011. Seasonal forecasting of tuna habitat for dynamic spatial management. Canadian Journal of Fisheries and Aquatic Sciences 68: 898-911.

Hobday, A. J., Dowling, N., Evans, K., Fulton, B., Kenyon, R., Lenton, A., Matear, R., Smith, D. C., Thompson, P. and van Putten, I. 2016. Inquiry into the impacts of climate change on marine fisheries and biodiversity. Senate Standing References Committee on Environment and Communications, CISRO Oceans and Atmosphere: 39p.

Holsman, K.K., Samhouri, J., Cook, G., Hazen, E., Olsen, E., Dillard, M., Kasperski, S., Gaichas, S., Kelble, C.R., Fogarty, M., and Andrews, K. 2017. An ecosystem-based approach to marine risk assessment. Ecosystem Health and Sustainability 3(1):e01256.

Hunter, K. and Wade, J. 2015. Pacific large aquatic basin climate change impacts, vulnerabilities and opportunities assessment – marine species and aquaculture. Canadian Manuscript Report Fisheries and Aquatic Science. No. 3049, viii + 252 p.

Ianelli, J. N., Kotwicki, S., Honkalehto, T., Holsman, K. and Fissel, B. 2017. Chapter 1: Assessment of the Walleye Pollock Stock in the Eastern Bering Sea (draft). North Pacific Fishery Managment Council Bering Sea and Aleutian Islands SAFE: 55-183.

ICCAT Secreteriat 2017a. Report of the 2017 ICCAT Atlantic Swordfish Stock Assessment Session. 3-7 July, Madrid: 85p.

ICCAT Secreteriat 2017b. Report of the 2017 ICCAT Bluefin Stock Assessment Meeting. 20-28 July, Madrid: 106p.

ICES 2001. Report of the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy. 4-13 September 2001, Copenhagen, Denmark: 360-421.

ICES 2005. Report of the Working Group on the Assessment of Mackerel, Horse Mackerel, Sardine and Anchovy (WGMHSA). 6-15 September 2005: 615p.

ICES 2016a. ICES Ecosystems Overview: Barents Sea Ecoregion. ICES Advice 2016, Book 9: 12p.

ICES 2016b. ICES Ecosystems Overview: Bay of Biscay and the Iberian Coast Ecoregion. ICES Advice 2016, Book 7: 15p.

ICES 2016c. ICES Ecosystems Overview: Celtic Seas Ecoregion. ICES Advice 2016, Book 5: 16p.

ICES 2016d. ICES Ecosystems Overview: Great North Sea Ecoregion. ICES Advice 2016, Book 6: 22p.

ICES 2016e. AORAC - SA FAO workshop: Making the ecosystem approach operational. Copenhagen, DK, 21-22 January: 55p.

ICES 2017a. Report of the Baltic Fisheries Assessment Working Group. ICES Advisory Committee. ICES CM 2017/ACOM:11. 810 p.

ICES 2017b. ICES Ecosystems Overview: Icelandic Waters Ecoregion. ICES Advice 2017, 3107: 19p.

ICES 2017c. ICES Ecosystems Overview: Norwegian Sea Ecoregion. ICES Advice 2017, 3108: 15p.

Kaplan, I. C., Williams, G. D., Bond, N. A., Hermann, A. J. and Siedlecki, S. A. 2016. Cloudy with a chance of sardines: forecasting sardine distributions using regional climate models. Fisheries Oceanography 25: 15-27.

Karnauskas, M., Kelble, C. R., Regan, S., Quenée, C., Allee, R., Jepson, M., Freitag, A., Craig, J. K., Carollo, C., Barbero, L., Trifonova, N., Hanisko, D. and Zapfe, G. 2017. 2017 Ecosystem status report update for the Gulf of Mexico: 51p.

King, J.R., McFarlane, G.A., and Punt, A.E. 2015. Shifts in fisheries management: adapting to regime shifts. Philosophical Transactions of the Royal Society B-Biological Sciences 370 http://dx.doi.org/10.1098/rstb.2013.0277.

Kleisner, K.M., Fogarty, M.J., McGee, S., Hare, J.A., Moret, S., Perretti, C.T. and Saba, V.S. 2017. Marine species distribution shifts on the US Northeast Continental Shelf under continued ocean warming. Progress in oceanography, 153: 24-36.

Kronlund, A.R., Cox, S.P., and Cleary, J.S. 2012. Management strategy evaluation in R (mseR): user’s guide and simulation exercises. Canadian Technical Report Fisheries and Aquatic Science. 3001: vii + 52 p.

Kumar, R., Pitcher, T. J. and Varkey, D. A. 2017. Ecosystem approach to fisheries: Exploring environmental and trophic effects on Maximum Sustainable Yield (MSY) reference point estimates. PLoS One12(9):e0185575. doi: 10.1371/journal.pone.0185575.

Laugen, A.T., Engelhard, G.H., Whitlock, R., Arlinghaus, R., Dankel, D.J., Dunlop, E.S., Eikeset, A.M., Enberg, K., Jorgensen, C., Matsumura, S., Nussle, S., Urbach, D., Baulier, L., Boukal, D.S., Ernande, B., Johnston, F.D., Mollet, F., Pardoe, H., Therkildsen, N.O., Uusi-Heikkila, S., Vainikka, A., Heino, M., Rijnsdorp, A.D., and Dieckmann, U. 2014. Evolutionary impact assessment: accounting for evolutionary consequences of fishing in an ecosystem approach to fisheries management. Fish and Fisheries 15:65-96.

de Lestang, S., Caputi, N., How, J., Melville-Smith, R., Thomson, A. and Stephenson, P. 2012. Stock Assessment for the West Coast Rock Lobster Fishery, Department of Fisheries, Western Australia: 200p.

Levin, P. S., Wells, B. K. and Sheer, M. B. E. 2013. California Current Integrated Ecosystem Assessment: Phase II Report.

Lindegren, M. and Brander, K. 2018. Adapting fisheries and their management to Climate Change: a review of concepts, tools, frameworks, and current progress toward implementation. Reviews in Fisheries Science and Aquaculture: DOI:10.1080/23308249.2018.1445980.

Link, J. S., Griffis, R. B. and Busch, S. E. 2015. NOAA Fisheries Climate Science Strategy, U.S. Dept. of Commerce, 70 p.

Mullon, C., Steinmetz, F., Merino, G., Fernandes, J. A., Cheung, W. W. L., Butenschön, M. and Barange, M. 2016. Quantitative pathways for Northeast Atlantic fisheries based on climate, ecological–economic and governance modelling scenarios. Ecological Modelling 320: 273-291.

Myers R.A. 1998. When do environment-recruitment correlations work? Reviews in Fish Biology and Fisheries 8: 285-305.

National Oceanic and Atmospheric Administration 2018. The California Current Integrated Ecosystem Assessment. Retrieved 20 March 2018.

North Pacific Fishery Management Council 2007. Draft Report of the Scientific and Statistical Committee. Anchorage, Alaska North Pacific Fishery Management Council: 31p.

Northeast Fisheries Science Center 2014. 58th Northeast Regional Stock Assessment Workshop (58th SAW) Assessment Report. National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, US Department of Commerce: 784p.

Northeast Fisheries Science Centre 2017a. 62nd Northeast Regional Stock Assessment Summary Report. National Marine Fisheries Service, 166 Water Street, Woods Hole, MA 02543-1026, US Department of Commerce, Northeast. Fisheries Science Center Reference Document: 1-261.

Northeast Fisheries Science Centre 2017b. Ecosystem Status Report for the Northeast Large Marine Ecosystem. NOAA Fisheries Service, 166 Water Street, Woods Hole, MA 02543. File modified on Dec 12, 2017. Accessed 28 Mar, 2018.

Ogier, E. M., Davidson, J., Fidelman, P., Haward, M., Hobday, A. J., Hollbrook, N. J., Hoshino, E. and Pecl, G. T. 2016. Fisheries management approaches as platforms for climate change adaptation: Comparing theory and practice in Australian fisheries. Marine Policy 71: 82-93.

Pacific Fishery Management Council 2013. Pacific Coast Fishery Ecosystem Plan for the U.S. Portion of the California Current Large Marine Ecosystem. 7700 NE Ambassador Place, Suite 101, Portland, Oregon 97220, Pacific Fishery Management Council: 190p.

Payne, M. 2018. Blue Whiting Spawning Habitat Forecast Sheet, ICES WGS2D Forecast Sheet 01-v03.0.

Pestal, G., Huang, A-M., Cass, A. and the FRSSI Working Group. 2012. Updated Methods for Assessing Harvest Rules for Fraser River Sockeye Salmon (*Oncorhynchus nerka*). DFO Can. Sci. Advis. Sec. Res. Doc. 2011/133. viii + 175 p.

Peterson, W.T., Fisher, J. L., Morgan, C.A., Burke, B. J., Zeman, S. M., and Jacobson, K. C. 2017. Ocean Ecosystem Indicators of Salmon Marine Survival in the Northern California Current. Accessed March 29, 2018.

PIFSC 2016. West Hawa'i'i Integrated Ecosystem Assessment: Ecosystem Trends and Status Report., NOAA Fisheries Pacific Science Center: 47p.

Pinsky, M.L. and Fogarty, M. 2012. Lagged social-ecological responses to climate and range shifts in fisheries. Climatic change, 115:883-891.

Plagányi, É. E., van Putten, I., Hutton, T., Deng, R. A., Dennis, D., Pascoe, S., Skewes, T. and Campbell, R. A. 2013. Integrating indigenous livelihood and lifestyle objectives in managing a natural resource. Proceedings of the National Academy of Sciences 110: 3639-3644.

Plagányi, É., Skewes, T., Dowling, N. and Haddon, M. 2013. Risk management tools for sustainable fisheries management under changing climate: a sea cucumber example. Climatic Change 119: 181-197.

Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P.J., Brander, K., Bruno, J.F., Buckley, L.B., Burrows, M.T., Duarte, C.M., Halpern, B.S., Holding, J., Kappel, C. V, O'Connor, M.I., Pandolfi, J.M., Parmesan, C., Schwing, F., Thompson, S.A. and Richardson, A.J. 2013. Global imprint of climate change on marine life. Nature Climate Change, 3: 919–925.

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. S. 2014. "Fisheries management under climate and environmental uncertainty: control rules and performance simulation. ICES Journal of Marine Science 71: 2208-2220.

Rosenberg, A.A., Kleisner, K.M., Afflerbach, J., Anderson, S.C., Dickey-Collas, M., Cooper, A.B., Fogarty, M.J., Fulton, E.A., Gutiérrez, N.L., Hyde, K.J. and Jardim, E. 2018. Applying a new ensemble approach to estimating stock status of marine fisheries around the world. Conservation Letters, 11:1-9.

Sagar, H., Larsen, K., Osgood, K. and Ford, M. E. 2016. NOAA Fisheries Ecosystem-Based Fisheries Management Road Map: 50p.

Saha, S., Moorthi, S., Pan, H.-L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y.-T., Chuang, H.-y., Juang, H.-M. H., Sela, J., Iredell, M., Treadon, R., Kleist, D., Delst, P. V., Keyser, D., Derber, J., Ek, M., Meng, J., Wei, H., Yang, R., Lord, S., Dool, H. v. d., Kumar, A., Wang, W., Long, C., Chelliah, M., Xue, Y., Huang, B., Schemm, J.-K., Ebisuzaki, W., Lin, R., Xie, P., Chen, M., Zhou, S., Higgins, W., Zou, C.-Z., Liu, Q., Chen, Y., Han, Y., Cucurull, L., Reynolds, R. W., Rutledge, G. and Goldberg, M. 2010. The NCEP Climate Forecast System Reanalysis. Bulletin of the American Meteorological Society 91: 1015-1058.

Saha, S., Nadiga, S., Thiaw, C., Wang, J., Wang, W., Zhang, Q., Dool, H. M. V. D., Pan, H.-L., Moorthi, S., Behringer, D., Stokes, D., Peña, M., Lord, S., White, G., Ebisuzaki, W., Peng, P. and Xie, P. 2006. The NCEP Climate Forecast System. Journal of Climate 19: 3483-3517.

Senate Environment and Communications References Committee 2017. In hot water: the impacts of climate change on marine fisheries and biodiversity. PO Box 6100, Parliament House, Canberra ACR 2600, The Senate: 144p.

Shackell, N.L., Greenan, B.J.W., Pepin, P., Chabot, D., and Warburton, A. 2013. Editors. Climate change impact, vulnerabilities and opportunities analysis of the marine Atlantic Basin. Canadian Manuscript Report Fisheries and Aquatic. Science. 3012: xvi + 366 p.

Shackell, N. L., Ricard, D., and Stortini, C. 2014. Thermal habitat index of many Northwest Atlantic temperate species stays neutral under warming projected for 2030 but changes radically by 2060. PLoS ONE, 9: e90662. https://doi.org/10.1371/journal.pone.0090662.

Siddon, E. and Zador, S. E. 2017. Ecosystem Considerations 2017: Status of the Eastern Bering Sea Marine Ecosystem. Auke Bay Laboratories, 17109 Pt. Lena Loop Road, Juneau, AK 99801, Alaska Fisheries Science Centre, National Marine Fisheries Service, NOAA: 231p.

Skern-Mauritzen, M., Ottersen, G., Handegard, N. O., Huse, G., Dingsør, G.E., Stenseth, N. C. and Kjesbu, O. S. 2016. Ecosystem processes are rarely included in tactical fisheries management. Fish and Fisheries 17: 165–175.

Slater, W. L., DePiper, G., Gove, J. M., Harvey, C. J., Hazen, E. L., Lucey, S. M., Karnauskas, M., Regan, S. D., Siddon, E. C., Yasumiishi, E. M., Zador, S. G., Brady, M. M., Ford, M. D., Griffis, R. B., Shuford, R. L., Townsend, H. M., O'Brien, T. D., Peterson, J. O., Osgood, K. E. and Link, J. S. 2017. Challenges, Opportunities and Future Directions to Advance NOAA Fisheries Ecosystem Status Reports (ESRs): Report of the National ESR Workshop: 66p.

Spies, I. T., Wilderbuer, D., Nichol D., Hoff, J. and Palsson, W. 2016. Chapter 6. Assessment of the Arrowtooth flounder stock in the Eastern Bering Sea and Aleutian Islands. NPFMC Bering Sea and Aleutian Island SAFE, North Pacific Fishery Management Council: 1015-1090.

Standing Committee on Research and Statistics 2014. 2015-2020 SCRS Science Strategic Plan. Strategic Plan Report: 323-343.

Stortini, C. H., Shackell, N. L., Tyedmers, P., and Beazley, K. 2015. Assessing marine species vulnerability to projected warming on the Scotian Shelf, Canada. ICES Journal of Marine Science 72: 1731–1743.

Szuwalski C.S. and Hollowed A.B. 2016. Climate change and non-stationary population processes in fisheries management. ICES Journal of Marine Sciences 73:1297-1305.

Thompson, G. G. 2017. 2. Assessment of the Pacific Cod Stock in the Eastern Bering Sea. North Pacific Fishery Management Council Bering Sea and Aleutian Islands SAFE: 229-516.

Tommasi, D., Stock, C. A., Alexander, M. A., Yang, X., Rosati, A. and Vecchi, G. A. 2017. Multi-Annual Climate Predictions for Fisheries: An Assessment of Skill of Sea Surface Temperature Forecasts for Large Marine Ecosystems. Frontiers in Marine Science 4(201): 13p. 10.3389/fmars.2017.00201.

Trenberth, K. E. and Hurrell, J. W. 1994. Decadal atmosphere-ocean variations in the Pacific. Climate Dynamics 9: 303-319.

Wertheimer, A. C., Orsi, J. A. and Fergusson, E. A. 2015. Forecasting pink salmon harvest in southeast Alaska from juvenile salmon abundance and associated biophysical parameters: 2014 returns and 2015 forecast. Auke Bay Laboratories, Ted Stevens Marine Research Institute, National Marine Fisheries Service (NMFS), National Oceanic and Atmospheric Administration (NOAA), NPFAC Doc 1618: 25p.

Whitehouse, A. and Zador, S. 2016. Ecosystem Considerations 2015: Preliminary Assessment of the Alaska Arctic. 7600 Sand Point Way NE, Seattle, WA 98115, Alaska Fisheries Science Centre, National Marine Fisheries Service, NOAA: 58-66.

Zador, S. E. 2016. Ecosystem Considerations 2016: Status of the Aleutian Islands Marine Ecosystem. 7600 Sand Point Way NE, Seattle, WA 98115, Alaska Fisheries Science Centre, National Marine Fisheries Service, NOAA: 110p.

Zador, S. and Yasumiishi, E. 2017. Ecosystem Considerations 2017: Status of the Gulf of Alaska Marine Ecosystem. North Pacific Fishery Management Council, 605 West 4th Ave., Suite 306, Anchorage, AK 99501. 213 p.

Zwolinski, J.P. and Demer, D.A. 2014. Environmental and parental control of Pacific sardine (*Sardinops sagax*) recruitment. ICES Journal of Marine Science 71: 2198–2207.

APPENDICES

Appendix A. List of stocks assessments considered in this review. DFO regions are Newfoundland and Labrador (NL), Quebec (Q), Gulf (G), Maritimes (M), Central and Arctic (CA) and Pacific (P). Transboundary (TRAC) stocks for which DFO provides advice were also included.

Category	Region	Common name	Latin name	Stock	Year
Anadromous	CA	Arctic Char	*Salvelinus alpinus*	Northwest Territories	2016
Anadromous	CA	Arctic Char	*Salvelinus alpinus*	Nunavut	2014
Anadromous	CA	Arctic Char	*Salvelinus alpinus*	Cambridge Bay	2013
Anadromous	CA	Arctic Char	*Salvelinus alpinus*	Exploratory Fisheries in Cumberland Sound	2010
Anadromous	CA	Arctic Char	*Salvelinus alpinus*	Cumberland Sound	2018
Anadromous	CA	Arctic Char	*Salvelinus alpinus*	Cambridge Bay	2018
Anadromous	CA	Arctic Char	*Salvelinus alpinus*	Lauchaln River	2018
Anadromous	NL	Atlantic Salmon	*Salmo salar*	SFAs 1-14B	2017
Anadromous	G	Atlantic Salmon	*Salmo salar*	SFA 15-18	2014
Anadromous	NL, M, G, Q	Atlantic salmon	*Salmo salar*	SFA 1-21, portion of SFA23, Quebec regions 1-10	2017
Anadromous	P	Chinook Salmon	*Oncorhynchus tshawytscha*	Southern BC	2016
Anadromous	P	Chinook Salmon	*Oncorhynchus tshawytscha*	Cowichan River, Barkley Sound	2017
Anadromous	P	Coho Salmon	*Oncorhynchus kisutch*	Southern BC	2017
Anadromous	P	Coho Salmon	*Oncorhynchus kisutch*	Interior Fraser River- status assessment	2017
Anadromous	P	Coho Salmon	*Oncorhynchus kisutch*	Interior Fraser River- evaluating harvest options	2017
Anadromous	CA	Lake Whitefish	*Coregonus clupeaformis*	Northwest Territories	2015

Category	Region	Common name	Latin name	Stock	Year
Anadromous	P	Pink Salmon	*Oncorhynchus gorbuscha*	Fraser River	2017
Anadromous	P	Sockeye Salmon	*Oncorhynchus nerka*	Fraser River- forecast of run size	2017
Anadromous	P	Sockeye Salmon	*Oncorhynchus nerka*	Fraser River- forecast of timing and diversion rate	2017
Anadromous	P	Sockeye Salmon	*Oncorhynchus nerka*	Fraser River-forecast of in-river losses	2016
Anadromous	P	Sockeye Salmon	*Oncorhynchus nerka*	Fraser River-status assessment	2013
Anadromous	P	Sockeye Salmon	*Oncorhynchus nerka*	Fraser River-evaluation of harvest control rules	2012
Anadromous	P	Sockeye Salmon	*Oncorhynchus nerka*	Okanagan River- forecast of run size	2017
Anadromous	P	Sockeye Salmon	*Oncorhynchus nerka*	Okanagan River- forecast of timing	2003
Anadromous	P	Sockeye Salmon	*Oncorhynchus nerka*	Barkley Sound/Alberni Inlet- forecast of run size	2017
Anadromous	P	Sockeye Salmon	*Oncorhynchus nerka*	Barkley Sound/Alberni Inlet- in-season harvest	2017
-	-	-	-	-	-
Elasmobranchs	P	Big Skate	*Bathyraja bionculata*	4B; 3CD, 5AB; 5CDE	2013
Elasmobranchs	P	Longnose Skate	*Raja rhina*	4B; 3CD, 5AB; 5CDE	2013
Elasmobranchs	P	Pacific Spiny Dogfish	*Squalus suckleyi*	Inside (4B); Outside (3CD5ABCDE)	2010
Elasmobranchs	M	Porbeagle shark	*Lamna nasus*	Subareas 3-6	2005
Elasmobranchs	M	Spiny Dogfish	*Squalus acanthias*	4VWX5+3P	2014

Category	Region	Common name	Latin name	Stock	Year
Elasmobranchs	NL	Thorny Skate	*Amblyraja radiata*	3Ps	2013
Elasmobranchs	NL	Thorny Skate	*Amblyraja radiata*	3Ps and 3LNO	2012
Groundfish	NL	American Plaice	*Hippoglossoides platessoides*	3LNO	2010
Groundfish	NL	American Plaice	*Hippoglossoides platessoides*	3Ps	2014
Groundfish	NL	American Plaice	*Hippoglossoides platessoides*	2J3K	2003
Groundfish	G	American Plaice	*Hippoglossoides platessoides*	Southern Gulf of St. Lawrence (4T)	2016
Groundfish	P	Arrowtooth Flounder	*Atheresthes stomias*	Coastwide (excluding 4B)	2017
Groundfish	Q	Atlantic Halibut	*Hippoglossus hippoglossus*	4RST	2015
Groundfish	M	Atlantic Halibut	*Hippoglossus hippoglossus*	3NOPS4VWX5Zc	2015
Groundfish	NL, M, G, Q, CA	Atlantic Wolffish	*Anarhichus lupus*	Northwest Atlantic and Arctic	2015
Groundfish	P	Canary rockfish	*Sebastes pinniger*	coastwide	2006
Groundfish	NL	Cod	*Gadus morhua*	2J3KL	2016
Groundfish	NL	Cod	*Gadus morhua*	3NO	2010
Groundfish	NL	Cod	*Gadus morhua*	3Ps	2017
Groundfish	G	Cod	*Gadus morhua*	Southern Gulf of St. Lawrence (4T and 4Vn)	2015
Groundfish	Q	Cod	*Gadus morhua*	3Pn, 4RS	2015
Groundfish	M	Cod	*Gadus morhua*	4X5Y	2016
Groundfish	TRAC	Cod	*Gadus morhua*	5Zjm; 551, 552, 561, 562	2016
Groundfish	TRAC	Greenland Halibut	*Reinhardtius hippoglossoides*	23KLMNO	2010
Groundfish	TRAC	Greenland Halibut	*Reinhardtius hippoglossoides*	NAFO SA0	2016

Category	Region	Common name	Latin name	Stock	Year
Groundfish	Q	Greenland Halibut	*Reinhardtius hippoglossoides*	4RST	2014
Groundfish	NL	Haddock	*Melanogrammus aeglefinus*	3LNO	2014
Groundfish	NL	Haddock	*Melanogrammus aeglefinus*	3Ps	2014
Groundfish	M	Haddock	*Melanogrammus aeglefinus*	4X5Y	2017
Groundfish	TRAC	Haddock	*Melanogrammus aeglefinus*	5Zjm; 551, 552, 561, 562	2016
Groundfish	NL	Hagfish	*Myxine glutonosa*	3Px	
Groundfish	P	Lingcod	*Ophiodon elongatus*	4B	2014
Groundfish	P	Lingcod	*Ophiodon elongatus*	3CD; 5AB; 5CD; 5E	2009
Groundfish	Q	Lumpfish	*Cyclopterus lumpus*	3Pn, 4Rs	2016
Groundfish	Q	Lumpfish	*Cyclopterus lumpus*	3Pn, 4RS	2016
Groundfish	NL	Monkfish	*Lophius americanus*	3LNOPs	2003
Groundfish	M	Monkfish	*Lophius americanus*	4VWX5Zc	2002
Groundfish	NL, M, G, Q, CA	Northern Wolffish	*Anarhichus denticulatus*	Northwest Atlantic and Arctic	2015
Groundfish	P	Pacific Cod	*Gadus macrocephalus*	5AB and 5CD	2014
Groundfish	TRAC	Pacific hake	*Merluccius productus*	California Current migratory stock	2016
Groundfish	TRAC	Pacific Halibut	*Hippoglossus stenolepsis*	Coastwide (Can-US)	2017
Groundfish	P	Pacific Ocean Perch	*Sebastes alutus*	5ABC	2017
Groundfish	P	Pacific Ocean Perch	*Sebastes alutus*	5CDE	2013
Groundfish	P	Pacific Ocean Perch	*Sebastes alutus*	3CD	2013
Groundfish	NL	Pollock	*Pollachius virens*	3Ps	

Category	Region	Common name	Latin name	Stock	Year
Groundfish	M	Pollock	*Pollachius virens*	4VWX+5	2009
Groundfish	P	Redbanded Rockfish	*Sebastes babcocki*	Coastwide (excluding 4B)	2017
Groundfish	NL	Redfish	*Sebastes mentella,fasciatus,marinus*	SA2,Div3k	2001
Groundfish	NL	Redfish	*Sebastes mentella,fasciatus,marinus*	3O	2000
Groundfish	NL,Q	Redfish	*Sebastes viviparus*	Units 1 and 2 (~3Pn and 4Vn)	2016
Groundfish	NL, M, G, Q	Redfish	*Sebastes mentella,fasciatus,marinus*	Unit 1-3; Focus on Unit3	2017
Groundfish	P	Rock sole	*Lepidopsetta spp.*	5AB; 5CD	2016
Groundfish	P	Sablefish	*Anoplopoma fimbria*	coastwide	2010
Groundfish	P	Sablefish	*Anoplopoma fimbria*	coastwide--note this is a SAR update for the 2011 MSE with analyses determing previous MP are not robust and should be revised	2017
Groundfish	P	Shortspine Thornyhead	*Sebastolobus alascanus*	Coastwide (excluding 4B)	2017
Groundfish	M	Silver Hake	*Merluccius bilinearis*	4VWX	2017
Groundfish	P	Silvergray Rockfish	*Sebastes brevispinis*	Coastwide	2014
Groundfish	NL, M, G, Q, CA	Spotted Wolffish	*Anarhichus minor*	Northwest Atlantic and Arctic	2015
Groundfish	NL	White Hake	*UROPHYCIS TENUIS*	3Ps	2016
Groundfish	G	Winter Flounder	*Pseudopleuronectes americanus*	4T	2012
Groundfish	NL	Witch Flounder	*Glyptocephalus cynoglossus*	3Ps	2013
Groundfish	G	Witch Flounder	*Glyptocephalus cynoglossus*	4RST	2012

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Groundfish	P	Yelloweye rockfish	*Sebastes ruberrimus*	4B	2010
Groundfish	M	Yellowtail and Plaice	*Limanda ferruginea*	4VW	2002
Groundfish	TRAC	Yellowtail flounder	*Limanda ferruginea*	5Zjm; 551, 552, 561, 562	2016
Groundfish	G	Yellowtail Founder	*Limanda ferruginea*	4T	2016
Invertebrate	NL	American Lobster	*Homarus americanus*	LFAs 3-14	2016
Invertebrate	G	American Lobster	*Homarus americanus*	LFA 23, 24, 25, 26A and 26B	2014
Invertebrate	Q	American Lobster	*Homarus americanus*	LFAS 19, 20 and 21 (Gaspé)	2017
Invertebrate	Q	American Lobster	*Homarus americanus*	LFAS 15-18 (North Shore and Anticosti Island)	2017
Invertebrate	Q	American Lobster	*Homarus americanus*	LFA 22 (Magdalen Islands)	2017
Invertebrate	M	American Lobster	*Homarus americanus*	LFA 27-33	2011
Invertebrate	M	American Lobster	*Homarus americanus*	LFA41,4X,5Zc	2017
Invertebrate	M	Arctic Surfclam	*Mactromeris Polynyma*	Banquereau bank	2017
Invertebrate	M	Arctic Surfclam	*Mactromeris Polynyma*	Grand Bank	2011
Invertebrate	Q	Atlantic Surfclam	*Spisula solidissima*	4T (Îles-de-la-Madeleine)	2016
Invertebrate	P	Dungeness crab	*Metacarcinus magister*	Crab management areas E, G and H	2015

Category	Region	Common name	Latin name	Stock	Year
Invertebrate	P	Geoduck	*Panopea generosa*		2008
Invertebrate	P	Geoduck	*Panopea generosa*	Update in estimation stock index methods	2017
Invertebrate	P	Green Sea urchin	*Strongylocentrotus droebachiensis*	Areas 12&13; Areas 18&19	2008
Invertebrate	Q	Green Sea urchin	*Strongylocentrotus_droebachiensis*	Northern Estuary and Gulf of St Lawrence	2016
Invertebrate	M	Green Sea Urchin	*Strongylocentrotus droebachiensis*	LFA36	2010
Invertebrate	M	Green Sea Urchin	*Strongylocentrotus droebachiensis*	LFA38	2010
Invertebrate	M	Jonah Crab	*Cancer borealis*	LFA 41	2009
Invertebrate	M	Lobster	*Homaris americanus*	LFA 34	2013
Invertebrate	M	Lobster	*Homaris americanus*	LFA 35-38	2013
Invertebrate	NL	Northern Shrimp	*Pandalus borealis*	SFA 4-6	2017
Invertebrate	CA	Northern Shrimp	*Pandalus borealis*	Western and Eastern Assessment Zones	2017
Invertebrate	Q	Northern Shrimp	*Pandalus borealis*	SFA 8, 9, 10, 12	2015
Invertebrate	M	Northern Shrimp	*Pandalus borealis*	SFA 13-15	2017
Invertebrate	P	Pink Scallop	*Chlamys rubida*	coastwide	2010
Invertebrate	G	Rock Crab	*Cancer Irroratus*	23, 24, 25, 26A & 26B	2008
Invertebrate	NL	Scallop	*Placopecten magellanicus*	3Ps	2016
Invertebrate	G	Scallop	*Placopecten magellanicus*	Area 21A-C,22-24	2011

Category	Region	Common name	Latin name	Stock	Year
Invertebrate	Q	Scallop	*Placopecten magellanicus*	4RST	2016
Invertebrate	Q	Scallop	*Placopecten magellanicus*	Subarea 20A (Magdalen Islands)	2017
Invertebrate	M	Scallop	*Placopecten magellanicus*	5Z,BrownsBank	2016
Invertebrate	M	Scallop	*Placopecten magellanicus*	Area 29	2015
Invertebrate	M	Scallop	*Placopecten magellanicus*	(SPAs) 1A, 1B, and 3 to 6	2016
Invertebrate	NL	Sea Cucumber	*Cucumaria frondosa*	3Ps	2017
Invertebrate	P	Sea Cucumber	*Parastichopus californicus*	coastwide	2007
Invertebrate	Q	Sea Cucumber	Cucumaria frondosa	Inshore	2017
Invertebrate	P	Sidestriped Shrimp	*Pandalopsis dispar*	inshore	2008
Invertebrate	P	Smooth Pink Shrimp	*Pandalus jordani*	offshore	2008
Invertebrate	P	Smooth Pink Shrimp	*Pandalus jordani*	inshore	2008
Invertebrate	NL	Snow Crab	*Chionoecetes opilio*	2J3KLNOPs	2016
Invertebrate	G	Snow Crab	*Chionoecetes opilio*	Gulf of St. Lawrence areas 12, 19. 12E, 12F (4T)	2017
Invertebrate	G	Snow Crab	*Chionoecetes opilio*	Areas 12, 19, 12E and 12F	2014
Invertebrate	Q	Snow Crab	*Chionoecetes opilio*	Areas 12a, 12b, 12c, 16a, and 13-17	2017
Invertebrate	Q	Snow Crab	*Chionoecetes opilio*	AREAS 13 TO 17, 12A, 12B, 12C AND 16A	2016
Invertebrate	M	Snow Crab	*Chionoecetes opilio*	4VWX	2015
Invertebrate	Q	Softshell Clam	*Mya arenaria*	Quebec coastal waters	2017
Invertebrate	P	Spiny Pink Shrimp	*Pandalus borealis*	inshore	2008

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Invertebrate	P	Spiny Scallop	*Chlamys hastata*	coastwide	
Invertebrate	P	Spot prawns	*Pandalus playceros*	coastwide	2008
Invertebrate	Q	Stimpson's Surfclam	*Mactromeris polynyma*	NorthCoastMagIslands	2015
Invertebrate	NL	Striped Shrimp	*Pandalus montagui*	SFA4	2017
Invertebrate	CA	Striped Shrimp	*Pandalus montagui*	Western and Eastern Assessment Zones	2017
Invertebrate	NL	Whelk	*Buccinum undatum*	3Ps	2013
Mammal	CA	Atlantic Walrus	*Odobenus rosmarus rosmarus*	West Jones Sound	2013
Mammal	CA	Atlantic Walrus	*Odobenus rosmarus rosmarus*	Baffin Bay	2013
Mammal	CA	Atlantic Walrus	*Odobenus rosmarus rosmarus*	Penny Strait-Lancaster Sound	2013
Mammal	CA	Atlantic Walrus	*Odobenus rosmarus rosmarus*	Foxe Basin (North and Central stocks)	2016
Mammal	CA	Atlantic Walrus	*Odobenus rosmarus rosmarus*	Hudson Bay-Davis Strait	2016
Mammal	CA	Atlantic Walrus	*Odobenus rosmarus rosmarus*	South East Hudson Bay	2016
Mammal	CA	Bearded seal	*Erignathus barbatus*	Northwest Territories, Nunavut	
Mammal	Q	Beluga	*Delphinapterus leucas*	St. Lawrence river estuary (4S)	2014
Mammal	CA	Beluga	*Delphinapterus leucas*	Northwest Territories, Nunavut	2016
Mammal	CA	Bowhead Whale	*Balaena mysticetus*	Northwest Territories, Nunavut	2008
Mammal	Q	Grey Seal	*Halichoerus grypus*	Southern Gulf of St. Lawrence, Scotian Shelf	2011
Mammal	Q	Grey Seal	*Halichoerus grypus*	Southern Gulf of St. Lawrence, Scotian Shelf	2011
Mammal	TRAC	Harp Seal	*Pagophilus groenlandicus*	Northwest Atlantic Harp Seals	2014

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Mammal	CA	Narwhal	*Monodon monoceros*	Nunavut	
Mammal	TRAC	Northern Fur Seal	*Callorhinus ursinus*	North Pacific	2011
Mammal	P	Pacific Harbour Seal	*Phoca vitulina richardsi*	Canadian Pacific waters	2009
Mammal	CA	Ringed seals	*Pusa hispida*	Northwest Territories, Nunavut	
Mammal	P	Sea Otter	*Enhydra lutris*	Canadian Pacific waters	2009
Mammal	P	Stellar Sea Lion	*Eumetopias jubatus*	Canadian Pacific waters	2008
Pelagic	TRAC	Albacore tuna	*Thunnus alalunga*	North Pacific	2015
Pelagic	M	Alewife	Alosa pseudoharengus,	Gaspareau River	2007
Pelagic	Q	Atlantic Mackerel	*Scomber scombrus*	NW Atlantic Subareas 3 and 4	2013
Pelagic	P	Bocaccio	*Sebastes paucispinis*	coastwide	2011
Pelagic	NL	Capelin	*Mallotus villosus*	2J3KL	2016
Pelagic	Q	Capelin	*Mallotus villosus*	4RST	2013
Pelagic	NL	Herring	*Clupea harengus*	South and East coast of NL	2017
Pelagic	G	Herring	*Clupea harengus*	4T-SpringSpawner	2016
Pelagic	G	Herring	*Clupea harengus*	4T-FallSpawners	2016
Pelagic	Q	Herring	*Clupea harengus harengus*	4R (E-GSL)	2014
Pelagic	Q	Herring	*Clupea harengus harengus*	4S	2011
Pelagic	M	Herring	*Clupea harengus harengus*	4VWX	2015
Pelagic	P	Pacific Herring	*Clupea pallasi*	HG; PRD; CC; SOG; WCVI; Area 2W; Area 27	2014
Pelagic	TRAC	Pacific Sardine	*Sardinops sagax*	Coastwide	2013