Collect. Vol. Sci. Pap. ICCAT, 81(4), SCRS/2024/081: 1-11 (2024)

# INCORPORATING CLIMATE CONSIDERATIONS INTO FISHERIES ASSESSMENTS AND MANAGEMENT ADVICE AT ICCAT

Nathan G. Taylor[1] and John F. Walter, III[2]

*SUMMARY*

*Climate Change impacts on fish stocks may include changes in ecological interactions, spatial redistribution, and changes in productivity. Predicting precisely what will happen to fish stocks with any future climate changes is challenging. Climate Change science could be used in the assessment process a) using indicator-based approaches to provide qualitative context; b) explicitly including climate change in stock assessments and using resulting forecasts to derive TAC advice; and/or c) explicitly including climate change in Management Strategy Evaluation to develop climate-ready management procedures. Among other conclusions, we argue that developing management procedures, tested and communicated through MSE, may be the best approach to addressing future uncertainties. Incorporation of climate linkages in operating model reference grids will allow for MPs to be tuned and selected specifically for climate-change readiness. Operating model climate linkages can be implicit (simply allowing for changes in the spawner-recruit relationship) or explicit (clear mechanistic link to a process). Linking directly to mechanistic processes will be more intensive and may involve an expanded set of collaborations with physical and ecosystem scientists.*

*RÉSUMÉ*

*Les effets du changement climatique sur les stocks de poissons peuvent inclure des changements dans les interactions écologiques, la redistribution spatiale et les changements de productivité. Il est difficile de prédire avec précision ce qu'il adviendra des stocks de poissons en cas de futurs changements climatiques. La science du changement climatique pourrait être utilisée dans le processus d'évaluation a) en utilisant des approches basées sur des indicateurs pour fournir un contexte qualitatif ; b) en incluant explicitement le changement climatique dans les évaluations des stocks et en utilisant les prévisions qui en résultent pour formuler l'avis sur les TAC ; et/ou c) en incluant explicitement le changement climatique dans l'évaluation de la stratégie de gestion pour développer des procédures de gestion (MP) adaptées au climat. Entre autres conclusions, nous soutenons que l'élaboration de procédures de gestion, testées et communiquées par le biais de la MSE, peut constituer la meilleure approche pour faire face aux incertitudes futures. L'intégration des liens climatiques dans les grilles de référence des modèles opérationnels permettra d'ajuster et de sélectionner les MP en fonction du changement climatique. Les liens climatiques des modèles opérationnels peuvent être implicites (simple prise en compte des changements dans la relation reproducteur-recrue) ou explicites (lien mécaniste clair vers un processus). L'établissement d'un lien direct avec les processus mécanistes sera plus intensif et pourra impliquer un ensemble élargi de collaborations avec des scientifiques spécialistes de la physique et de l'écosystème.*

*RESUMEN*

*Los efectos del cambio climático en los stocks de peces pueden incluir cambios en las interacciones ecológicas, la redistribución espacial y los cambios en la productividad. Predecir con exactitud qué ocurrirá con los stocks de peces en caso de cambios climáticos futuros es todo un reto. La ciencia del cambio climático podría utilizarse en el proceso de evaluación: a) utilizando enfoques basados en indicadores para proporcionar un contexto cualitativo; b) incluyendo explícitamente el cambio climático en las evaluaciones de stocks y utilizando las previsiones resultantes para formular el asesoramiento sobre los TAC; y/o c) incluyendo*

[1] ICCAT Secretariat, Madrid, Spain. nathan.taylor@iccat.int
[2] NOAA Fisheries. Southeast Fisheries Science Center, Miami, FL. john.walter@noaa.gov

*explícitamente el cambio climático en la evaluación de estrategias de ordenación para desarrollar procedimientos de ordenación (MP) preparados para el clima. Entre otras conclusiones, sostenemos que el desarrollo de procedimientos de ordenación, probados y comunicados a través de la MSE, puede ser el mejor enfoque para hacer frente a futuras incertidumbres. La incorporación de vínculos climáticos en las matrices de referencia de los modelos operativos permitirá ajustar y seleccionar los MP específicamente por su preparación frente al cambio climático. Los vínculos climáticos del modelo operativo pueden ser implícitos (simplemente permiten cambios en la relación reproductor-recluta) o explícitos (vínculo mecanicista claro con un proceso). La vinculación directa con los procesos mecanicistas será más intensiva y puede implicar un conjunto ampliado de colaboraciones con científicos físicos y de los ecosistemas.*

*KEYWORDS*

*Natural mortality, simulation, climate data, environmental factors, ecosystem management, genetics, geographic distribution, pelagic ecosystems*

*Caveat*

*The views expressed in this paper are that of the authors and not of either the ICCAT Secretariat, the United States National Marine Fisheries Service, our respective employers, or the SCRS, the scientific body we work under at ICCAT. We provide this paper as a food for thought to foster dialogue at this meeting*

## 1. Statement of the problem

Climate change forecasts predict substantial impacts on tuna stocks (Muhling *et al*. 2017, Erauskin-Exramiana *et al* 2023), but like with any projections into the future, we do not know with certainty the nature, direction, or magnitude of such changes nor do we necessarily know the most appropriate management responses. Such effects might include changes in ecological interactions, spatial redistribution, and changes in reproductive output. A confounding factor is that attached to a natural system in flux, is an equally complicated management system that has imposed layers of complexity on attributing changes to fishing or environmental factors. While there may be a small number of successes, the history of fisheries science at being able to infer how fish stocks respond to environmental changes reliably is poor. The history of the discipline is replete with examples of the debate between the relative roles of environmental factors and fishing: for Pacific halibut Thompson and Burkenroad argued passionately on the subject (Skud, 1975), engaging a broad set of experts in the debate in 1940s and 1950s so that it is considered one of the most intense in the fisheries literature (Quinn 2003). After the moratorium on the Newfoundland cod in 1992, there are still debates about the relative role of overfishing and stock assessment error (Walters and MacGuire 1996), changes in natural mortality (Myers and Cadigan 1995, Hutchings 1996), ecological interactions (Walters and Kitchell 2001, Shelton and Harley 1999) and environmental effects (Brander 2019; Brander 2005); and there are similar debates for small pelagic fish like Sardine (Giron-Nava *et al.* 2021) and anchovy (Fréon *et al.* 2008; Hilborn and Walters 1992, Clark 1976). While it might be possible to make valid predictions of oceanographic changes with climate change, predicting what is likely to happen to fish stocks with any future climate changes is challenging.

***Climate change potential for non-stationarity in population dynamics***

Looking at history may not help improve scientific inference. Most ICCAT stock assessments consist of using time-series data within a model to estimate key parameters. These two unobservable leading parameters are typically a productivity parameter that defines how recruits change with biomass, and an initial biomass or initial recruitment parameter that defines the theoretical biomass or number of recruits in an unfished state (Walters and Martell 2005, Hilborn and Walters 1992). Catch and relative indices of abundance like Catch Per Unit Effort (CPUE) are used in a statistical procedure that varies the unknown parameters until their values are the most probable given the data. These estimated parameters determine the historical and current biomass as well as the status of the stock relative to reference points like Maximum Sustainable Yield, MSY. Climate change signifies that these leading parameter estimates (and other parameters) should not be expected to be the same in the future as they were in the past. Defined more formally, it means that the properties of the statistical distributions (for example, the mean and variance) are changing over time. Beyond the leading parameters, under climate change it is reasonable to expect that there will also be changes in other key stock assessment inputs (growth, stock and recruitment, natural mortality) and/or stock distribution. Indeed, changes in weight at age and/or natural mortality have been observed in assessments for some fisheries like Pacific herring (DFO 2019, Pacific Hake (Johnson *et al.* 2021), and Pacific halibut (IPHC 2022) where these changes alone are responsible for significant proportion of the biomass decline in recent years. In narrow single-species assessment terms, non-stationarity in growth and natural mortality means changes in the theoretical unfished biomass and maximum sustained yield. In broad terms, non-stationarity means that key processes are not constant and that the past may not reliably predict future states.

## 2. What do we do?

While dedicated research can help us understand how key climate variables (temperature, current changes, etc.) affect fish stocks, this does not necessarily tell us what the most appropriate management response should be. ICCAT has been successful in managing stocks under the stock assessment and resulting Kobe management advice framework, but this relies upon being able to calculate biological reference points and project probable future conditions to generate the Kobe 2 strategy matrix. However, climate change represents an 'unknown unknown' situation where the future state of the ecosystem is unknown and the future human behavioral responses are even more unknown (Walter *et al.* 2023). This is precisely the situation where decision support tools such as Management Strategy Evaluation could be valuable for decision making under uncertainty regarding climate change.

Recent Management Strategy Evaluations (deLeMar 1998, Smith 1999; Punt *et al.* 2016) at ICCAT have developed management procedures for albacore and bluefin tuna and are ongoing for swordfish and tropical tunas. Several of these provide examples of how ICCAT can develop management procedures that might more explicitly consider climate and other future environmental changes. Exploratory closed-loop simulation of harvest strategies have also been used for sharks (Taylor *et al.* 2022a, Taylor *et al.* 2022b). As non-stationarity (changing environmental baselines) challenges our ability to predict the future, scientific advice may increasingly rely on developing management procedures that are simulation tested to meet objectives for stock safety, status, and fishery stability independent of a set potential future state of the ecosystem.

Inasmuch as MSE is a practical change in the science and stock assessment it is also an important change in the conceptual formulation of the stock assessment and management problem. To illustrate the difference, we use a financial analogy. In this analogy, the best assessment paradigm consists of trying to estimate the amount of money in a bank account. Unlike a real bank account, the balance (the stock size), the withdrawals, the deposits, and the rate of return are only partly observable. Starting with the opening balance (the unobservable unfished biomass) the assessment annually subtracts known withdrawals from account (the catches), it assumes a certain proportion account balance is also taken from the account by other people (the natural mortality), and it credits the account with deposits (the observable changes in size at age, and the unobservable recruitment). In analogy, the counterpoint to estimating the bank account balance (the best assessment) is to figure out an investment strategy given uncertain market yields and conditions (i.e., MSE). Returns on specific investment instruments are highly uncertain and potentially non-stationarity. Importantly, in the world of investment, the ability to reliably predict returns on investment and the worldwide financial situation is poor. Given the unpredictability of the markets, most investors adopt *strategies* to allow them to cope with market variability as opposed to predicting what might happen. Similarly, for MSE the focus should be on what strategies will be robust for addressing climate change.

## 3. What are the potential elements that ICCAT needs to consider for adapting fisheries stock assessment and management for climate change?

While the theoretical basis for MSE is useful for developing strategies to address climate change, the problem should be viewed with a broader lens than adopting single species management procedures. Just as in a single species MSE, it will involve strategic decisions about which data will be used, methods used to analyze those data, and how those analysis will be converted into a harvest recommendation or policy. However, in climate change scenarios, the types of data, analysis, and harvest control rules may be expanded from standard stock assessment data. It is easy to claim that Operating Models should be developed to consider climate change but it is hard to include explicit mechanistic linkages to climate impacts and harder still to assign degrees of plausibility to such scenarios.

The US fisheries management councils organized a workshop dedicated precisely to addressing the question of how to adapt fisheries management to climate change (Hollowed, A. and D. Stram (eds). 2023). The workshop's agenda provides a useful outline which ICCAT could consider tackling this problem. It consisted of 3 focus sessions:

1. How to incorporate ecosystem indicators into the stock assessment process
2. Developing information to support management of interacting species in consideration of the Ecosystem Based Fisheries Management
3. How to assess and develop fishing level recommendations for species exhibiting distributional changes due to climate variability and Climate Change

A key message from this workshop and numerous studies and empirical applications is that just because we can incorporate ecosystem indicators into stock assessment does not mean that we always should. In the Pacific herring and halibut examples mentioned above, there are annual age composition time series starting before 1950 and survey series beginning in the1950s and 1970s respectively. Accordingly, there was a very strong basis in data to account for apparent changes in size at age for those stocks. In the herring case, it also made it possible to estimate time-varying natural mortality. Including time-varying growth and time-varying natural mortality resulted in substantially reduced estimates of the unfished biomass that was used in the harvest control rule (Hall *et al.* 1988). Using the model with these time-varying effects did not go well: the attempt to reopen fisheries that had previously been closed under this harvest control was met with litigation (Haida Nation v. Canada (Fisheries and Oceans), 2015 FC 290 (CanLII), Ahousaht First Nation v. Canada (Fisheries and Oceans), 2014 FC 197) that the management agency ultimately lost.

The herring story is too long to address here, but one factor of many in the conflict was that the harvest control rule that was being applied had not been tested under the circumstances (Operating Models) that stock found itself i.e., non-stationary growth and non-stationary natural mortality. The other main factor was that the efficacy of an assessment model (a component of the Management Procedure) that was used with time-varying growth and natural mortality had not been tested as part of the Management Procedure that was already implemented either. The main lesson from the herring case is that just being able to include time-varying effects in a stock assessment does not necessarily imply that the result will be better management outcomes. Management Procedures, whether they include ecosystem or climate indicators or not, need to be tested, and the results of that process need to be communicated before being applied. Testing through Management Strategy Evaluation offers an additional benefit of involving stakeholders in the process both for elucidating operational management objectives, generating plausible climate hypotheses given their traditional knowledge of the system, and coproduction of climate-ready management procedures.

With respect to stock specific ecosystem indicators, the more prosaic issue is that much of the basic data necessary to detect anticipated changes in life history parameters has been unavailable historically. There is no history of routine age-composition collation for any stocks that could support any inference about time-varying changes in body size at age or natural mortality. Many of the modeling predictions of climate change predict decreases in size or weight at age (Erauskin-Extramiana *et al.*, 2023). Hence obtaining and processing the basic data (age, growth, size/weight at age and reproductive information) may require regular, augmented data collection programs.

In addition to Operating Model development that includes changes in predicted productivity changes, there are Management Procedures that are already developed to capture productivity changes (Collie *et al.* 2021). Provided that they are tested, testing such procedures offers a way to see if productivity changes can be estimated so that climate change effects on productivity can be included explicitly in a Management Procedure. Productivity changes need not necessarily be estimated, others have argued that a simple fixed harvest rate management procedure is robust to climate change (Walters and Parma 1996) or that simpler assessment models are robust to decadal changes (Parma 2002). Whatever the management procedure, the important thing is to develop it to be able to handle likely future scenarios.

## 4. How could climate change be included in the ICCAT scientific process?

There are at least three ways that climate change science could be used in the scientific assessment process at ICCAT, ranging from qualitative to having direct impacts on resulting TAC advice as follows below.

a. *Indicator-based approaches to provide qualitative context.* The ICCAT Ecosystems working group has developed a series of indicators to describe the state of the ecosystem. These provide useful context for understanding trends in the ecosystem, formulating hypotheses on potential impacts and considerations for management decisions beyond just TACs, however there currently is little formal incorporation of such information into the quantitative advice framework at ICCAT. Moreover, using indicators to make inference about communities is fraught and especially so for non-targeted species (Polachek 2007, Kleiber and Maunder 2008).

b. *Explicitly include climate change in the stock assessment and resulting forecasts used to derive TAC advice*. Currently there is little scientific consensus as to how to explicitly include environmental considerations into stock assessments. There is a rather checkered history of doing so and Punt 2023 argues that to defend against the possibility of including spurious correlations, there needs to be a formal way of including climate change indicators in the stock assessment process. While it is relatively straightforward to include environmental factors in the CPUE standardization and this is routinely done at ICCAT, using environmental factors to drive major processes (mortality, recruitment, spatial distribution) and projections is much less well-developed, primarily because it is challenging to determine the actual mechanism by which the environment may drive population dynamics. In addition, correlations with processes such as annual recruitment often break down over time (Zwolinski & Demer, 2019, Myers 1998, McClatchie *et al.* 2010, Jacobson & McClatchie 2010). Western Atlantic Bluefin tuna provides a good example for how challenging this has been for over 30 years as the TAC advice has been dependent upon whether one assumed that a regime shift in the spawner-recruit relationship has occurred or not, with science unable to provide a definitive answer (Porch and Lauretta 2013). Recent attempts at developing quantitative scoring for 'regime-shifts' (Klaer *et al.* 2015) provide some semi-objective guidance, however climate change may not result in a clearly differentiated 'regimes' as changes may be incremental and science may not provide a definitive answer in the timeframe necessary to make TAC decisions.

Punt 2023 offers several options for management advice considering non-stationarity in productivity, ranging from moving averages for recruitment, employing a dynamic B0 concept to explicit regime shifts in the stock recruitment relationship. Each has some benefits and some consequences (Szuwalski *et al* 2023) but, fundamentally, these considerations take the form of altering TAC advice based on assumptions about how the past dynamics have changed and how they may change into the future.

Given this, climate change poses a substantial challenge to science as, even under assumed stationarity, most assessment situations have difficulty estimating biomass reference points (Walters and Ludwig 1985, NRC 1998, Magnusson and Hilborn, R. 2007), so they will be further challenged to estimate moving targets and then predicting them into the future. One path forward is to manage for a fishing mortality reference point as adopted for bluefin tuna prior to the management procedure. The BFT Working Group noted that it could not give reliable biomass-based reference points and hence could not give status based on B/Bmsy. Rather the committee proposed an F01 fishing strategy that would have the expectation to rebuild or maintain the stock at the biomass that corresponds to the proxy for Fmsy, regardless of what future recruitment was. The committee also provided TAC advice based on recent average recruitment.

From a scientific perspective, we may need to consider that climate change may make estimating biomass-based status determinations very challenging. This might mean recognizing that providing recommendations for the variable that managers can control (i.e. the fishing mortality) may be the best option in an uncertain environment (Walters and Martell 2005).

c. *Explicitly include climate change in management strategy evaluation to develop climate-ready management procedures*

Given the challenges of explicitly including climate change into the stock assessment and projection process this may be the best process for incorporating climate considerations into developing robust (i.e. climate-ready) advice.

Climate considerations can enter MSE in at least three ways:

i. explicit climate-linked hypothesis informing the reference grid (grid of Operating Models used to tune and choose management procedures) Operating Models. The process would outline a series of hypotheses and plausibility weights for them in the reference grid. This is where the most likely or plausible climate-related scenarios would be incorporated into the reference grid.

ii. climate-linked hypotheses used for robustness tests. This would function as above; however, the climate-linked OMs would not be used to develop and tune management procedures but rather solely to screen them after tuning to determine whether the MPs work under less likely scenarios. This could be used to inform exceptional circumstances provisions or those situations where the MP is likely to fail.

iii. climate-informed management procedures. These include classes of management procedures that would have a specific climatic or environmental trigger to be included in the formula that determines the TAC. Such climate-explicit MPs rely on getting the mechanism behind the climate/environment impact on the population correct, which is particularly challenging.

For any of the scenarios in ii-iii we would recommend a scheme similar to Punt 2023 to guard against the possibility of including spurious climate or environmental considerations. One such scheme would be:

- identify parameters that may be time varying (at least in principle)
- identify hypotheses that have been postulated / speculated / tested linking environmental variables to these parameters.
- fit the operating model to the data (e.g., conditioning) to quantify the relationships between the environmental covariates and the parameters and to obtain model fits to different hypotheses.
- Examine impact of environmental linkage on management procedure performance- linkages without impact on performance need not be included in Operating Models. Often it is the case that environmental linkages are already manifest in the indices, so they do not need to be double counted.
- High plausibility environmental linkages with high impact should be included in reference grid OMs.
- Low plausibility environmental linkages with high impact can be relegated to robustness OMs.

A number of MSE projects consider climate change already. The swordfish MSE process explicitly considers variability in the stock recruitment (i.e., increased variability) as part of an Operating Model against which to test MSE and the BFT MSE explicitly considers regime shifts in the stock-recruitment relationship and both swordfish and BFT employ a dynamic B0 for reference point calculation within the MSE.

More comprehensive consideration of climate and environmental change in ICCAT science will benefit from external and interdisciplinary collaborations such as ICCAT's participation in the Global Environment Facility (GEF) Tuna Project. With respect to potential ecological interactions in ICCAT fisheries, ICCAT has a GEF project called ECOTEST that allows for testing the performance of ecological indicators. The computer software for ECOTEST was developed in 2022 (Hyun *et al.* 2022) and it should be continued through 2026. A second opportunity through GEF is to explore spatial changes in tuna distribution caused by climate change using a model called Seapodym (Lehodey *et al.* 2013, Lehodey *et al* 2015, Bell *et al*. 2021). This project is part of a broader set of projects including ECOTEST that aim explicitly to consider climate-change effects. While the Seapodym project is focused on Pacific stocks in the initial years of GEF, there is the potential to apply the methods to ICCAT stocks but only if ICCAT catch and effort data can be available at 1ºx1º resolution. Both these projects offer ways of developing Operating Models that could be used to test simple management procedures to determine which ones are robust to climate change but both may require data at resolutions that are not readily available.

Lastly, scientific advances such as advanced genomics offer the possibility to assess and possibly manage fisheries by harnessing their power and economies of scale. These allow the possibility of epigenetic aging, estimating total abundance or scale, estimating realized fecundity at age, natural mortality and possibly changes in mixing or movement rates. With increasing power, genomics will likely offer insights into numerous biological processes that may be affected by climate change such as genetic adaptation. Close-kin mark recapture (Bravington *et al.* 2016a, Bravington 2016b), is currently being explored for application in Atlantic bluefin tuna (McDowell *et al.* 2022) and gene tagging (Preece *et al.* 2018) is used to for the CCSBT management procedure and has been proposed for Atlantic bluefin tuna as a potential exploitation-rate based management procedure (Carruthers *et al*. 2023). Given the potential for epigenetic-based aging it may also be possible to obtain age composition non-invasively and more cost-effectively than using hard parts. Conventional gene tagging offers similar benefits to close-kin in that the methods estimate the current fishing mortality rate so that a simple management procedure such as fixed exploitation rate policies (Walters and Parma 1996) could be applied (Walters and Martell 2002). The key point with genetic techniques is that we need not limit our options to employing the same assessment techniques that have traditionally been used in assessments and that these genetics techniques help avoid some of the problems stock assessment has struggled with such as getting an accurate estimate of biomass (Magnusson and Hilborn 2007, NRC 1998, Ludwig and Walters 1986).

## 5. How could climate change be included in ICCAT management?

Management actions at an RFMO such as ICCAT span a range from TAC setting, allocations, size limits and seasons, bycatch mitigation and spatial management. Almost all of the actions identified in (4) above relate to informing TACs however, the potential impacts of climate change may have implications for many other management decisions (Karp *et al.* 2019, Boyce *et al.* 2020) which may require some specific 'rules' for management decisions (Link *et al*. 2021). For example, climate change is predicted to have substantial changes on species distributions (Lehodey *et al*. 2013, Lehodey *et al.* 2015, Bell *et al.* 2020); impacts we may be seeing already with bluefin tuna expanding their spatial distribution (Mckenzie *et al.* 2014). Such redistribution of the species may result in concomitant calls for reconsidering allocation. Furthermore, as ICCAT also approves fishing plans for each Contracting and Cooperating party as part of their collective management, climate change considerations could become part of such plans that could specifically include measures designed to reduce fuel consumption, carbon emissions and increase fishing efficiency (Erauskin-Extramiana *et al.* 2023), thereby allowing the fisheries to maintain profitability and stability in a shifting climate.

## 6. Points for consideration

One certainty we face is that the future is uncertain, yet climate change predictions for the world's oceans foretell very different conditions which will likely affect ICCAT-managed species both positively and negatively. Below, we offer some points for consideration as ICCAT tackles climate change:

- Developing climate-ready management procedures, tested and communicated through MSE may be the most expedient near-term approach to informing management actions in the face of climate uncertainties.
- Incorporation of climate linkages in the Operating Model reference grid will allow for MPs to be tuned and selected specifically for climate-readiness but it is not the only means of incorporating climate into MSE.
- Operating model climate linkages can be implicit (e.g. simply allowing for changes in the spawner-recruit relationship, natural mortality or other processes) or explicit (e.g. clear mechanistic link to a process). Linking directly to mechanistic processes will be more intensive and may involve an expanded set of collaborations with physical and ecosystem scientists.
- Given the rapid pace of anticipated changes to the system and the complexity of building mechanistically-linked process models, ICCAT cannot let 'perfect be the enemy of good' when it comes to developing adaptive management procedures.
- Detecting climate-related changes in productivity, spatial, and temporal distributions will require high quality fishery dependent data and/or independent surveys.
- Productivity changes often manifest as changes in size at age, weight at age or growth rates, which could be informed by increased systematic collection of size and age composition data from fisheries.
- The SCRS could consider a systematic process for including climate change indicators in the stock assessment process to avoid the inclusion of potentially spurious correlations.
- The SCRS may consider expanding projects nascent as part of GEF and others are used in other jurisdictions for application in ICCAT.
- Exploring broader use of genetic techniques for stock assessments and programs that would support the regular collection and analysis of such data will establish genetic baselines and may become assessment tools of the future to address uncertainties posed by climate change.
- ICCAT may want to define formal 'rules' to consider climate impacts on management decisions such as allocations, spatial and temporal management, and risk considerations.

## References


Boyce, D. G., Schleit, K., & Fuller, S. 2020. Incorporating Climate Change into fisheries management in Atlantic Canada and the Eastern Arctic. Halifax, Nova Scotia, Canada.

Bell, J. D., Senina, I., Adams, T., Aumont, O., Calmettes, B., Clark, S., Dessert, M., Gehlen, M., Gorgues, T., Hampton, J., Hanich, Q., Harden-Davies, H., Hare, S. R., Holmes, G., Lehodey, P., Lengaigne, M., Mansfield, W., Menkes, C., Nicol, S., Williams, P. 2021. Pathways to sustaining tuna-dependent Pacific Island economies during climate change. Nature Sustainability, 4(10), 900–910. https://doi.org/10.1038/s41893-021-00745-z

Brander, K. 2005. Cod recruitment is strongly affected by climate when stock biomass is low. Ices Journal of Marine Science - ICES J MAR SCI, 62, 339–343. https://doi.org/10.1016/j.icesjms.2004.07.029

Brander, K. 2019. Cod and Climate Change. In Atlantic Cod (pp. 337–384). https://doi.org/https://doi.org/10.1002/9781119460701.ch8

Bravington, M. V., Skaug, H. J., and Anderson, E. C. 2016a. Close-kin mark-recapture. Statistical Science, 31(2), 259–274. https://doi.org/10.1214/16-STS552

Bravington, M. V., Grewe, P. M., and Davies, C. R. 2016b. Absolute abundance of southern bluefin tuna estimated by close-kin mark-recapture. Nature Communications, 7, 1–8. https://doi.org/10.1038/ncomms13162

Butterworth, D. S. 2007. Why a management procedure approach? Some positives and negatives. ICES Journal of Marine Science, 64(4), 613–617.

Carruthers, T., Hyun, Q., Lauretta, M., Miller, S., Butterworth, D., Preece, A., Hordyk A., and Taylor, N.G. 2023. Evaluating Atlantic Bluefin Tuna Harvest Strategies that Use Conventional Genetic Tagging Data. Frontiers in Marine Science. Accepted for publication.

Clark, W. G. 1976. The lessons of the Peruvian anchoveta fishery. California Cooperative Oceanic Fisheries Investigation Reports, 19, 57–63. https://doi.org/10.1126/science.49.1274.501

Collie, J. S., Bell, R. J., Collie, S. B., and Minto, C. 2021. Harvest strategies for climate-resilient fisheries. ICES Journal of Marine Science, 78(8), 2774–2783. https://doi.org/10.1093/icesjms/fsab152

De la Mare, W. K. 1998. Tidier fisheries management requires a new MOP (management-oriented paradigm). Reviews in Fish Biology and Fisheries, 8(3), 349–356. https://doi.org/10.1023/A:1008819416162

DFO. 2019. Status of Pacific Herring (Clupea pallasii) in 2018 and forecast for 2019. Can. Sci. Advis. Sec. Sci. Resp. 2018/Nnn., 27(January), 1–38.

Erauskin-Extramiana, M., Chust, G, Arrizabalaga, H, Cheung, W.W.L., Santiago, J., Merino, G., Fernandes-Salvador, J. A. 2023. Implications for the global tuna fishing industry of climate change-driven alterations in productivity and body size. Global and Planetary Change. 222.

Fréon, P., Bouchon, M., Mullon, C., García, C., and Ñiquen, M. 2008. Interdecadal variability of anchoveta abundance and overcapacity of the fishery in Peru. Progress in Oceanography, 79(2–4), 401–412. https://doi.org/10.1016/j.pocean.2008.10.011

Hollowed, A. and D. Stram (editors). 2023. Seventh National Meeting of the Scientific Coordination Subcommittee. Report of the Regional Fishery Management Council's National SSC Workshop. North Pacific Fisheries Management Council, Anchorage, Alaska.

Hilborn, R., and Walters, C. J. 1992. Quantitative Fisheries Stock Assessment Choice, Dynamics and Uncertainty. Routledge, Chapman and Hall.

Hutchings, J. A. 1996. Spatial and temporal variation in the density of northern cod and a review of hypotheses for the stock's collapse. Canadian Journal of Fisheries and Aquatic Sciences, 53(5), 943–962. https://doi.org/10.1139/cjfas-53-5-943

Huynh, Q. C., Carruthers, T., and Taylor, N. G. 2022. ECOTEST, A Proof of Concept for Evaluating Ecological Indicators in Multispecies Fisheries, with the Atlantic Longline Fishery Case Study. Collect. Vol. Sci. Pap. ICCAT, 79(5): 165-177.

International Pacific Halibut Commission. 2023. Assessment of the Pacific halibut (*Hippoglossus stenolepis*) stock at the end of 2022. IPHC-2023-SA-01

Jacobson, L. D. and McClatchie, S. 2013 Comment on temperature-dependent stock-recruit modeling for Pacific sardine (*Sardinops sagax*) in Jacobson and MacCall (1995), McClatchie *et al.* (2010), and Lindegren and Checkley (2013). Can J. Fish. Aquat. Sci. 70, 1566–1569.

Johnson, K.F., A.M. Edwards, A.M. Berger and C.J. Grandin. 2021. Status of the Pacifc Hake (whiting) stock in U.S. and Canadian waters in 2021. Prepared by the Joint Technical Committee of the U.S. and Canada Pacific Hake/Whiting Agreement, National Marine Fisheries Service and Fisheries and Oceans Canada. 269 p.

Giron-Nava, A., Ezcurra, E., Brias, A., Velarde, E., Deyle, E., Cisneros-Montemayor, A. M., Munch, S. B., Sugihara, G., & Aburto-Oropeza, O. 2021. Environmental variability and fishing effects on the Pacific sardine fisheries in the Gulf of California. Canadian Journal of Fisheries and Aquatic Sciences, 78(5), 623–630. https://doi.org/10.1139/cjfas-2020-0010

Karp, M. A., Peterson, J. O., Lynch, P. D., Griffis, R. B., Adams, C. F., Arnold, W. S., Barnett, L. A. K. *et al*. 2019. Accounting for shifting distributions and changing productivity in the development of scientific advice for fishery management. ICES Journal of Marine Science, 76: 1305–1315.

Klaer, N. L., O'Boyle, R. N., Deroba, J. J., Wayte, S. E., Little, L. R., Alade, L. A., and Rago, P. J. 2015. How much evidence is required for acceptance of productivity regime shifts in fish stock assessments: Are we letting managers off the hook? Fisheries Research, 168, 49–55. https://doi.org/10.1016/j.fishres.2015.03.021

Kleiber, P., and Maunder, M. N. 2008. Inherent bias in using aggregate CPUE to characterize abundance of fish species assemblages. Fisheries Research, 93(1–2), 140–145. https://doi.org/10.1016/j.fishres.2008.03.013

Lehodey P., Senina I., Calmettes B, Hampton J, and Nicol S. 2013. Modelling the impact of climate change on Pacific skipjack tuna population and fisheries. Climatic Change, DOI 10.1007/s10584-012-0595-1, 119 (1): 95-109

Lehodey P., Senina I., Nicol S., and Hampton J. 2015. Modelling the impact of climate change on South Pacific albacore tuna. Deep Sea Research. 113: 246–259. doi:10.1016/j.dsr2.2014.10.028

Link, J.S., Karp, M.A., Lynch, P., Morrison, W.E., and Peterson, J. 2021. Proposed business rules to incorporate climate-induced changes in fisheries management. – ICES Journal of Marine Science 78(10), 3562–3580.

Mackenzie, B., Payne, M, Boje, J. Hoyer, J., Siegstad, H. 2014. A cascade of warming impacts brings bluefin tuna to Greenland waters. Global Change Biology 20, 2484–2491, doi: 10.1111/gcb.12597

McClatchie, S., Goericke, R., Auad, G. and Hill, K. 2010 Re-assessment of the stock–recruit and temperature–recruit relationships for Pacific sardine (*Sardinops sagax*). Can. J. Fish. Aquat. Sci. 67, 1782–1790.

Magnusson, A., and Hilborn, R. 2007. What makes fisheries data informative? Fish and Fisheries, 8(4), 337–358. https://doi.org/10.1111/j.1467-2979.2007.00258.x

McDowell, J.R., Bravington, M., Grewe, P.M. *et al.* 2022. Low levels of sibship encourage use of larvae in western Atlantic bluefin tuna abundance estimation by close-kin mark-recapture. Sci Rep 12, 18606. https://doi.org/10.1038/s41598-022-20862-9

Myers, R. A. 1998. When do environment–recruitment correlations work? Rev. Fish Biol. Fish. 8, 285-305.

Muhling, B., Lindegren, M., Clausen, L.W., Hobday, A., and Lehodey, P., 2017. Impacts of Climate Change on Pelagic Fish and Fisheries. Climate Change Impacts on Fisheries and Aquaculture: A Global Analysis, pp. 771–814.

National Research Council. Improving Fish Stock assessment. National Academy Press Washington, D.C. 1998

Parma, A. M. 2002. In Search of Robust Harvest Rules for Pacific Halibut in the Face of Uncertain Assessments and Decadal Changes in Productivity. Bulletin of Marine Science, 70(2), 423–453.

Polacheck, T. 2005. Tuna longline catch rates in the Indian Ocean : Did industrial fishing result in a 90 % rapid decline in the abundance of large predatory species? Marine Policy, 30(5), 470–482. https://doi.org/10.1016/j.marpol.2005.06.016

Porch CE, Lauretta MV (2016) On Making Statistical Inferences Regarding the Relationship between Spawners and Recruits and the Irresolute Case of Western Atlantic Bluefin Tuna (*Thunnus thynnus*). PLoS ONE 11(6): e0156767.

Preece, A. L., Eveson, P. J., Grewe, P.M., Bradford, R., Clear, N., Aulich, J., Lansdell, M., Cooper, S., Hartog, J. 2018. The 2018 SBT gene-tagging program. Commonwealth Scientific and Industrial Research Organisation (CSIRO). CCSBT-OMMP/2006/04. Available at: https://www.ccsbt.org/en/system/files/OMMP11_05_CCSBT_GT2018Program_DataForMPandOM.pdf [accessed December 2021]

Punt 2023. Including ecosystem information in assessments and management advice in Hollowed, A. and D. Stram (editors). 2023. Seventh National Meeting of the Scientific Coordination Subcommittee. Report of the Regional Fishery Management Council's National SSC Workshop. North Pacific Fisheries Management Council, Anchorage, Alaska.

Schreiber, M. A., Ñiquen, M., & Bouchon, M. 2011. Coping strategies to deal with environmental variability and extreme climatic events the Peruvian anchovy fishery. Sustainability, 3(6), 823–846. https://doi.org/10.3390/su3060823

Shelton, P. A., and Harley, B. P. 1999. Should depensation be dismissed as a possible explanation for the lack of recovery of the northern cod (*Gadus morhua*) stock? Canadian Journal of Fisheries and Aquatic Sciences, 56, 1521–1524.

Skud, B. E. 1975. Revised estimates of halibut abundance and the Thompson-Burkenroad debate. International Pacific Halibut Commission Scientific Report 56.

Szuwalski, C S., Hollowed, A B., Holsman, K K., Ianelli, J N., Legault, C M., Melnychuk, M C., Ovando, D., & Punt, A E. 2023. Unintended consequences of climate-adaptive fisheries management targets. Fish and Fisheries, 24, 439– 453. https://doi.org/10.1111/faf.12737

Taylor, N.G., Ortiz, M., Kimoto, A., Coelho. 2022a. Preliminary closed-loop simulations for Northeast Porbeagle Shark: Illustrating the efficacy of alternative Management Procedures and assessment frequency. Collect. Vol. Sci. Pap. ICCAT, 79(4): 216-230

Taylor, N.G., Ortiz, M., Kimoto, A., Coelho, R., Cortes E., and Forselledo, R., 2022b. The effect of nonlinear relationships between CPUE and abundance on the management procedure performance for the northeast porbeagle shark stock. Collect. Vol. Sci. Pap. ICCAT, 79(4): 231-239.

Walter, J F. III, C D Peterson, K Marshall, J J Deroba, S Gaichas, B C Williams, S Stohs, D Tommasi, R Ahrens. 2023. When to conduct, and when not to conduct, management strategy evaluations, ICES Journal of Marine Science, Volume 80, Issue 4, May 2023, Pages 719–727, https://doi.org/10.1093/icesjms/fsad031

Walters, C. J., Maguire, J.-J. 1996. Lessons for stock assessment from the northern cod collapse. Reviews in Fish Biology and Fisheries, 6, 125–137.

Walters, C. J., and Parma, A. 1996. Fixed Exploitation Rate Strategies for Coping with the Effects of Climate Change. Can. J. Fish. Aquat. Sci, 53, 148–158.

Walters, C., and Korman, J. 1999. Linking recruitment to trophic factors: revisiting the Beverton-Holt recruitment model from a life history and multispecies perspective. Rev. Fish Biol. Fish., 9, 187–202.

Walters, C., and Kitchell, J. F. 2001. Cultivation/depensation effects on juvenile survival and recruitment: implications for the theory of fishing. Can. J. Fish. Aquat. Sci, 581, 39–50. https://doi.org/10.1139/f00-160

Walters, C. and Martell S.J.D. 2002. Stock Assessment Needs for Sustainable Fisheries Management. Bulletin of Marine Sciences. 70(2):629-638s.

Walters, C. J., & Martell, S. J. D. 2004. Fisheries Ecology and Management. Princeton University Press.

Quin, T. J. Q. 2003. Ruminations on the Development and Future of Population Dynamics Models in Fisheries. Fisheries. 16, 341–392.

Zwolinski, J. P. & Demer, D. A. Re-evaluation of the environmental dependence of Pacific sardine recruitment. Fish. Res. 216, 120–125 (2019).