



# Horizon Scan on the Benefits of Ocean Seasonal Forecasting in a Future of Increasing Marine Heatwaves for Aotearoa New Zealand

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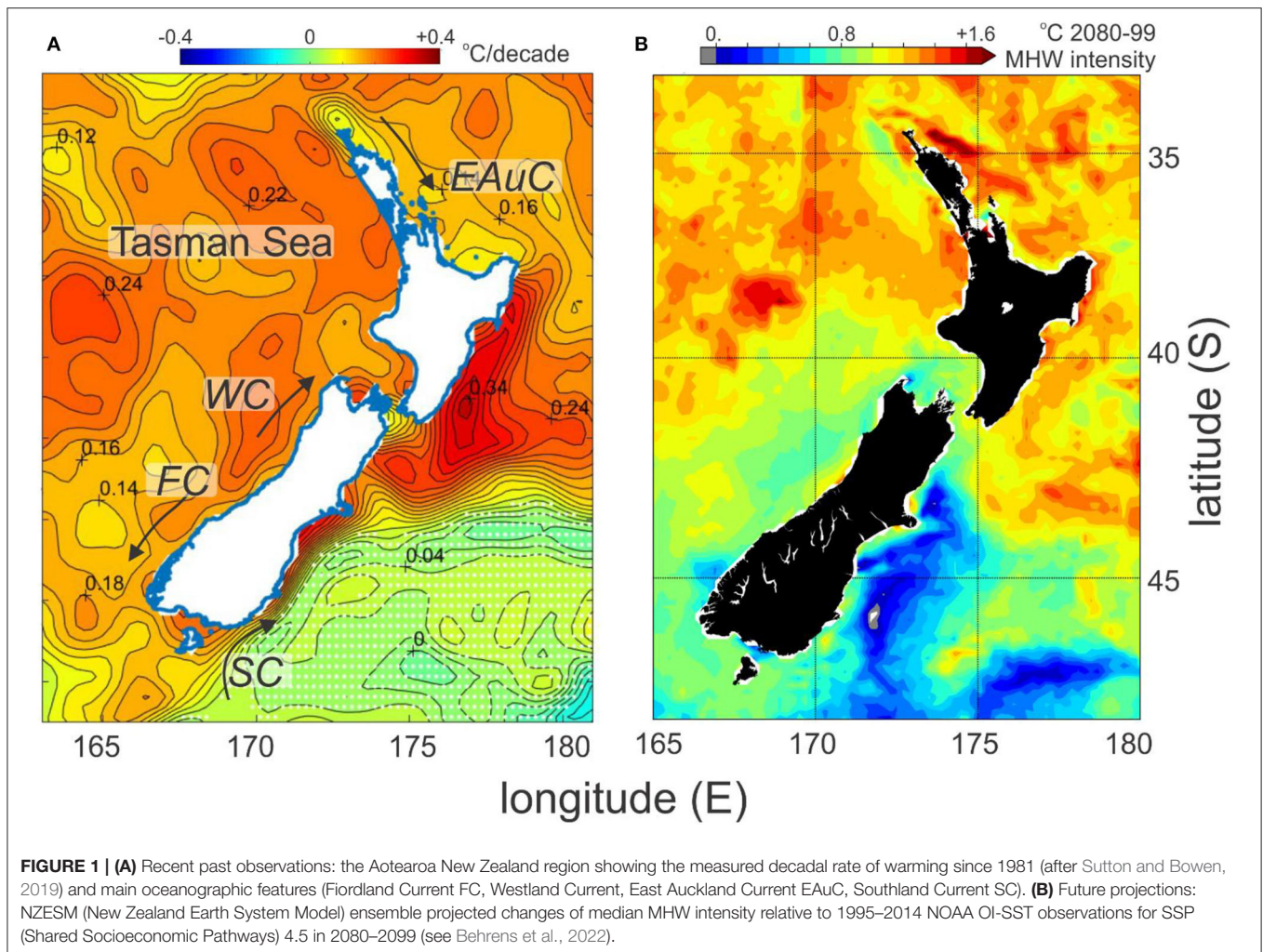
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With climate heating, Aotearoa New Zealand is expected to experience more marine heatwaves (MHW) in the coming decades. These extreme events are already impacting the island nation's marine and coastal environments and marine industries at a variety of scales. There will potentially be substantial benefits in developing an early warning system—specifically ocean seasonal forecast tools. This near-term 2,030 horizon scan reviews studies supporting the development of this capability and notes work needed to enable stakeholders to benefit from this knowledge. Review findings congregate around six themes; (1) MHW impacts, (2) mechanistic understanding, (3) observational basis, (4) seasonal forecast tools, (5) supporting Te Tiriti (The Treaty of Waitangi) and Māori aspirations, and (6) end-user engagement. The primary recommendation is a cross-institutional, cross-sector MHW Taskforce that would address, in a coordinated and effective fashion, the real, multi-faceted challenges associated with the committed pathway of warming. A range of sub-recommendations follow that connect with the United Nations Ocean Decade initiative.

**Keywords:** seasonal prediction, marine management, marine heatwaves, Tasman Sea, aquaculture, ocean observation, coastal communities, science strategy

## INTRODUCTION

The oceans around Aotearoa New Zealand (AoNZ) are, in some regions, warming at a rate well in excess of the global average (Sutton and Bowen, 2019; **Figure 1**). In addition to increased background warming, the most recent IPCC report on impacts provides high confidence that this region will become increasingly vulnerable to extreme ocean temperature events—marine heatwaves (MHWs), at a range of spatio-temporal scales (IPCC, 2022). A high-emission scenario earth system model (ESM) shows an increase between 80 and 100% of median MHW intensities, as well as MHW



conditions becoming permanent year-round, in the AoNZ region by 2100 (Figure 1; Behrens et al., 2022). AoNZ regularly experiences MHWs, with recent events (e.g., 2014/15, 2017/18; Salinger et al., 2020) exhibiting ocean temperatures several degrees above normal conditions (Behrens et al., 2019). These extreme events impact AoNZ marine environments and industries (e.g., aquaculture–IPCC, 2022) and are projected to become more frequent and severe (Behrens et al., 2022).

One adaptation strategy comprises reliable forewarning of these events. Ocean seasonal forecasting (OSF) can provide advance warning of MHWs and inform management responses to help mitigate impacts (Spillman et al., 2021). These forecasts provide information on key oceanic parameters up to 9 months into the future, bridging the gap between weather forecasts and climate projections. Forecasts on this timescale have been demonstrated to aid decision-making for marine managers in a variety of industries (e.g., Tommasi et al., 2017; Spillman and Smith, 2021).

While many regions globally are facing these challenges (Jacox et al., 2022), there are a number of special issues for AoNZ that warrant a horizon scan of OSF targeted at MHW prediction out

to 2030. This short time frame is both in response to the rapidly warming oceans around AoNZ (Sutton and Bowen, 2019), as well as alignment with United Nations Ocean Decade (UNOD) goals and framing (Ryabinin et al., 2019). When assessing the potential for benefits of OSF in AoNZ it is important to do so in the context of its unique geographic and socioeconomic setting. AoNZ is an isolated, relatively small landmass in a large ocean. It is a small-economy science system with minimal present investment in *in-situ* ocean data and capacity (Stevens and O’Callaghan, 2015). While the economic focus is on primary production, including marine, there is a high degree of social license required for marine industries to operate. In particular, the needs to take into account the principles of the Treaty of Waitangi (Te Tiriti o Waitangi), and kaitiakitanga (Waitangi Tribunal, 2011). In addition, this scan was motivated by a sector-wide review of the nation’s science system—the Te Ara Paerangi–Future Pathways Programme (Main, 2021).

The AoNZ “blue economy” which includes fisheries, aquaculture, minerals, fossil fuels, and transport, was estimated in 2019 to be worth 3% of GDP (Yeoman et al., 2019) with expectations for growth in some areas. For example,

the government aquaculture strategy (MPI, 2019) seeks to raise aquaculture production five-fold by 2035. Arguably, given the scale of the marine environment, other marine sectors could also increase their range and value, with a knowledge-driven engagement across multiple sectors being a starting point for that expansion (Smith et al., 2021). However, continued viability will be challenged significantly by climate change impacts on biodiversity which, in AoNZ, are primarily manifested in the marine environment (Keegan et al., 2022).

This horizon scan considers OSF in relation to six themes and associated recommendations: (1) MHW impacts, (2) mechanistic MHW understanding, (3) ocean observations, (4) current and future OSF tools, (5) Te Tiriti and supporting Māori aspirations, and (6) end-user engagement. Recommendations are aligned where possible with the UN Decade of the Ocean – Societal Outcomes and Research Priorities (UNOD, Ryabinin et al., 2019).

## THEMES

### Theme 1: MHW Impacts

MHWs in the AoNZ region have been clearly identified in recent years (e.g., 2017/18 and 2018/19–Salinger et al., 2019, 2020). MHWs can lead to altered species distributions (e.g., Thomsen et al., 2019), reductions in growth rates and fish production (e.g., Cheung and Frölicher, 2020), mortality events (e.g., Babcock et al., 2019), and harmful algal blooms (e.g., Oliver et al., 2017). Temperature is one of the strongest determinants of organism distribution (Kearney and Porter, 2009). While incremental changes in mean temperatures can force poleward range shifts in species, strong warming events such as MHWs can result in mass mortality and local extinctions of vulnerable species, which can have a cascade of effects on the marine ecosystem (e.g., Weatherdon et al., 2016; Wernberg et al., 2016; Tait et al., 2021). MHWs have also caused the collapse and/or closure of wild fisheries in recent years (e.g., Caputi et al., 2019). Caged fish farm production may be reduced if fish are stressed by unfavorable conditions (Islam et al., 2021; IPCC, 2022) and unusually warm waters have been implicated in shellfish crop failure (Keeling et al., 2014; Broekhuizen et al., 2021; King et al., 2021). While there may also be some positive impacts, in all these cases there are a range of complexities and uncertainties requiring more data and process understanding (Smith et al., 2021; Tait et al., 2021).

MHWs also have the capacity to influence terrestrial conditions and impact agricultural production, especially on an island nation such as AoNZ (e.g., Zheng and Frederiksen, 2006). The combined impacts of warming oceans and MHWs are affecting the human communities that use, value, and have stewardship over the marine environment in AoNZ. In addition, these impacts will be experienced disproportionately across society as disadvantaged groups of people have a greater degree of vulnerability to stresses on health and living conditions (Smith et al., 2021; Lawrence and Mackay, 2022). The resulting reductions in wellbeing will exacerbate poverty and widen the gap between wealthy and non-wealthy (IPCC, 2022).

### Recommendation:

1. *Implementation of a major shelf seas biophysical survey to improve understanding of biophysical connections and better account for future shifts in marine populations in response to evolving temperatures (UNOD Priority Area 3: A Quantitative Understanding of Ocean Ecosystems).*

### Theme 2: Mechanistic MHW Understanding

A sound mechanistic understanding of MHW, their drivers and outstanding challenges, and how they interact with largescale dynamics like El Niño and the Pacific Decadal Oscillation, is required to both produce skillful forecast tools at seasonal timescales (weeks to months), and identify which ocean observations are needed for forecast verification (Behrens et al., 2019; Chiswell, 2021). Critically, this will require improved understanding of coupling between offshore and nearshore extreme temperature events (“downscaling mechanics”); more specifically, assessments of the along- and across-shelf decorrelation scales of MHWs in shelf and offshore waters, and the factors that control these (de Souza et al., 2021).

Oceanic heat content in the Tasman Sea acts as a preconditioner of MHWs and is predictable at longer timescales than the atmospheric state (e.g., surface heat fluxes), making it a useful indicator and measure of the likelihood of MHWs. Fluctuations in ocean heat content in the Tasman Sea are predominantly controlled by oceanic meridional heat transport from the subtropics, which in turn is mainly characterized by the interplay of the East Australian Current and the Tasman Front (Sutton and Bowen, 2019). Shorter-term variability in these currents is impacted by wind anomalies north of the Tasman Sea region (Behrens et al., 2019). Deeper hydrography and heat content are also important as these combine to influence both biological production and sea surface temperature estimates (Behrens et al., 2019, 2022; Elzahaby et al., 2021).

### Recommendation:

2. *Increased support for multi-scale studies to identify and address knowledge gaps.*

### Theme 3: Ocean Observational Resources

While the satellite and Argo eras have significantly improved understanding of “bluewater” oceanography (Chiswell et al., 2015), the same cannot be said for coastal and shelf seas around AoNZ where marine industries typically operate (O’Callaghan et al., 2019). With limited surface satellite data due to cloud cover and few subsurface observations shallower than 1000 m, neither the baseline observations nor event-based variability of MHWs exists for AoNZ. Data paucity for AoNZ’s oceans is a major challenge. For example, there is nothing to compare with the Australian Integrated Marine Observing System (PCE, 2019) yet primary industry sectors recommend a connected, data platform that enables environmental decision making (PMCSA, 2021).

The benefits of observing MHWs provide *in situ* mechanistic knowledge of MHWs and improve parameterisation of upper ocean processes to increase model skill, and ultimately seasonal forecasts of MHWs. As these do not presently exist, sustained observations are critical to gain a dynamical understanding of

MHWs (Lo Bue et al., 2021). With both surface and subsurface MHW signals evident in the Tasman Sea (Youstina and Schaeffer, 2019), robotic sampling is proving valuable for event-based sampling (Testor et al., 2019). A regionally distributed suite of process-focused studies would connect shallower dynamics to measurement of changes in ocean heat content gained from Argo around AoNZ (Sutton and Bowen, 2019).

#### **Recommendations:**

3. **Improved ability to respond to observing MHW events to provide data both for improved understanding as well as for assimilation into forecasts. (UNOD Societal Outcome A predicted ocean).**
4. **Sustained and expanded ocean observational networks including deep ocean heat content through a suite of regional-focused studies (UNOD Priority Area 2: A Comprehensive Ocean Observing System).**

### **Theme 4: Future Seasonal Forecast Tools**

Seasonal dynamic forecast systems provide increasingly skillful predictions, both as individual prediction systems such as Australian Community Climate Earth System Simulator–Seasonal (ACCESS-S; de Burgh-Day et al., 2022), and multi-model ensemble syntheses such as Copernicus Climate Change Service Seasonal Forecasts (C3S; Hemri et al., 2019). Forecast accuracy will vary regionally and with season and lead time. Single-model, regionally focused forecast assessments can improve mechanistic understanding and potentially enhanced regional certainty (de Burgh-Day et al., 2019, 2022) whereas multi-model forecast ensembles provide a greater spread of projections and statistical evidence (Hobday et al., 2018a). Stakeholders tend to have a local and immediate view, so the viability of downscaling approaches (dynamical nesting, statistical, machine learning) is critical and a rapidly evolving complementary field of research (e.g., Ping et al., 2021; Taylor and Feng, 2022).

There is increasing demand for seasonal MHW forecasts (Spillman et al., 2021), especially those that are tailored to unique regional/local situations. It is important to also evaluate the added value of dynamic and statistical downscaling methods for improving the impact of seasonal MHW forecasts (e.g., Zheng and Frederiksen, 2006). Both points are motivated by there being a range of local oceanographic and atmospheric processes that can decouple the duration and intensity of local- from broad-scale MHWs (e.g., Schlegel et al., 2017). This decoupling may limit forecast skill and uptake of forecasts by end-users, if it is not accounted for in some manner.

#### **Recommendations:**

5. **Strengthen international linkages to both provide improved access to multi-model forecast ensemble forecast data and open pathways to contribute local ocean data into international projects (UNOD Societal Outcome - a transparent and accessible ocean).**
6. **Ensure computational infrastructure, capability and capacity to keep pace with growing volumes of data and model demands (UNOD Societal Outcome A predicted ocean).**

7. **Improve downscaling capability to connect large-scale forecasts to local scales through a systematic sequence of regional analyses (UNOD Societal Outcome A predicted ocean).**

### **Theme 5: Upholding Te Tiriti**

Given the 8-year timeline proposed here there is an expectation that established pathways for mātauranga Māori and Māori interest groups to inform and benefit from science will develop and grow. The clearest way to achieve this is to ensure a strong and early contribution to decision-making and governance from Māori scholars and advisors (e.g., Hudson et al., 2020). Te Tiriti-led governance and pathways for involvement include input from, and advice for, iwi/hapu resource managers, Māori-owned marine industries, Māori coastal communities, to generate mātauranga Māori-based mitigation responses as well as Māori-led science (e.g., Awatere et al., 2021).

The nation-scale climate research initiative The Deep South National Science Challenge supported a number of Māori-led climate-related projects which, to a large extent, focused on sea level rise and extreme weather issues (e.g., Stephenson et al., 2018) and so marine heatwaves remain an area of future emphasis. While the need for targeted research, capacity, and capability developments for the benefit of Māori are clear, it is not a straightforward pathway to achieve, given the heavy demands on the time of Māori researchers and the paucity of Te Tiriti-led marine and coastal governance and management.

Investment needs to be made to support and build capacity, both new and established, as well as improved approaches for mutually beneficial effective connections between mātauranga Māori and ocean science (Stevens et al., 2021), and their respective practitioners. In addition, work on Māori-focused climate-related topics is typically in the form of local case studies, reflecting the sense and value of place and community (e.g., McCarthy et al., 2014; Davies et al., 2018). Approaches to connect past and present understandings, as well as impacts on cultural values and Māori rights and interests, to the scales and content of future ocean forecasting delivery methods will need to be co-developed.

#### **Recommendations:**

8. **Ensure Te Tiriti o Waitangi-driven governance and co-management is a central pillar of development (UNOD Societal Outcome - a healthy and resilient ocean).**
9. **Support growth in capacity for Māori researchers and Māori communities (UNOD Societal Outcome - a transparent and accessible ocean).**

### **Theme 6: Enduser Engagement**

To benefit society, forecast metrics must be presented in a way that are useful, with end users able to understand and interpret the results, as well as provide feedback into their design (Hobday et al., 2016; Holbrook et al., 2020; Smith et al., 2021). The connectedness and scale of AoNZ suggests there is an opportunity to take a coordinated approach to working with coastal and marine-focused communities. In the coming decade it is anticipated that seasonal marine forecasts are relied on for

decision support in a similar way to weather forecasts (Stevens and O’Callaghan, 2015).

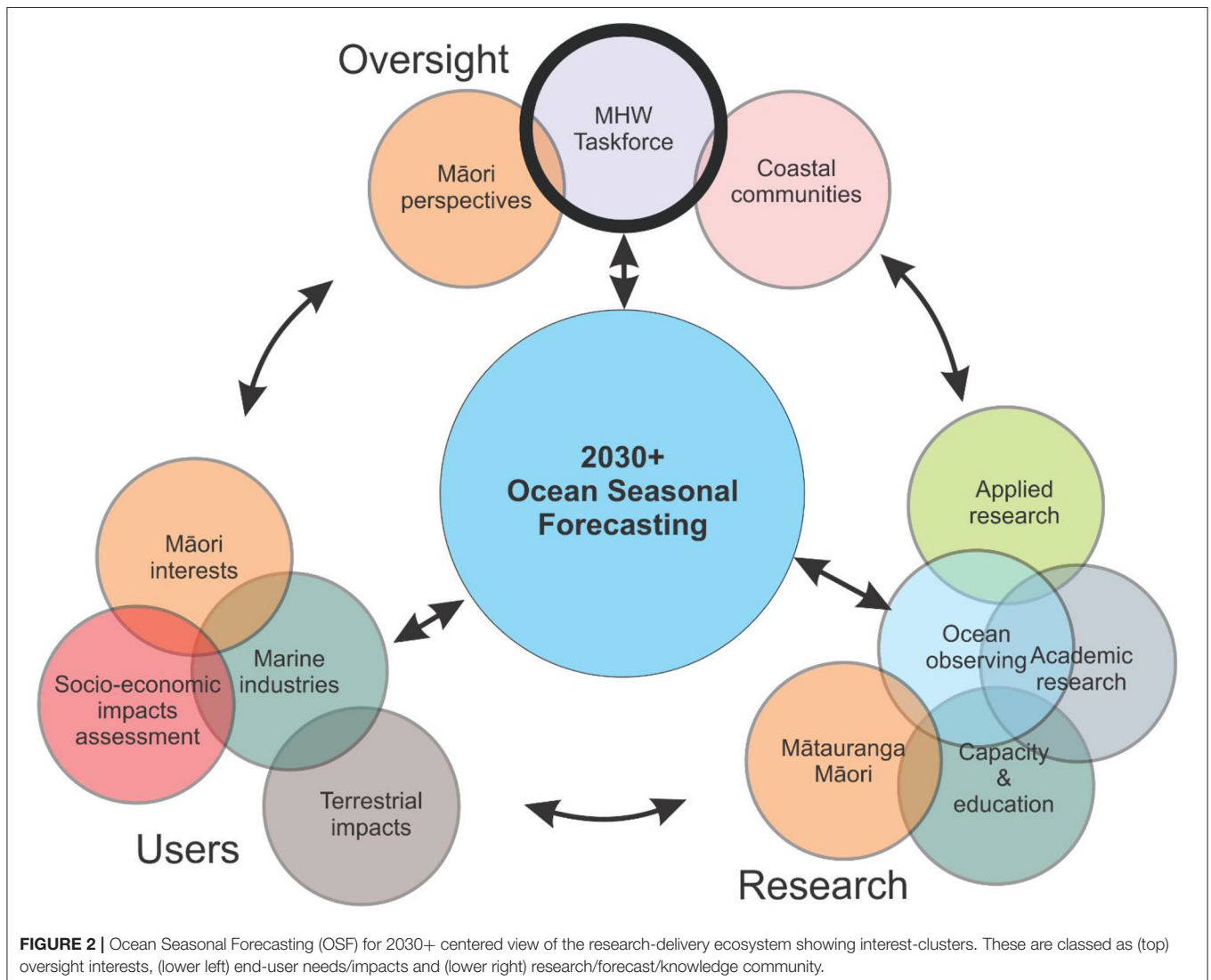
Taking the example of aquaculture as a leading marine activity in terms of how MHW impacts will be manifested, in AonZ. Most aquaculture operations are conducted at a regional scale. There are opportunities for regional seasonal forecasts to drive operational changes based on those forecasts (e.g., re-seeding density, timing and seed-sources, harvest times). An exception to this is mussel farming which relies heavily on juvenile spat from one region alone so that it would require operators to keep an eye on MHW projections for two regions in sequence.

In addition, industry-specific models could improve operational decision support (Hobday et al., 2018a,b). Better understanding of the link between MHW and storm frequency at a regional scale will also improve aquaculture operations, particularly for open ocean farms through identification of good operational conditions, harvest closures, and improved farm design (Heasman et al., 2020). These ideas extend to wild fisheries through improved stock assessment and fishery zoning

(Hobday et al., 2011). Effective communication, particularly around forecasted risk of an event and model skill, is key for both forecast uptake by end users and mitigation of MHW impacts. Marine industries and management agencies could benefit from employing MHW forecast tools, combined with tailored communication via apps and interactive visualization and feedback.

**Recommendations:**

10. *Co-develop with non-technical users forecast delivery mechanisms that enable the tailoring and delivery of highly technical information (UNOD Societal Outcome - a transparent and accessible ocean).*
11. *Develop evidence for the benefits of OSF by initiating a longitudinal case study which identifies sectors and communities that benefit from, and inform, future forecast delivery pathways (UNOD Priority Area 4: Data and Information Systems and UNOD Societal Outcome - a healthy and resilient ocean).*



## DISCUSSION

Each of the recommendations listed align with foci of the UN Decade of the Ocean (Ryabinin et al., 2019). The Future Pathways (Main, 2021) restructuring of the national science system is a significant opportunity for change in how actors interact through the formation of a taskforce to lead preparations, forecasting, and response for increasingly frequent MHW. This “MHW Taskforce” (Figure 2) would need to be able to unilaterally develop opportunities for users (communities, governance etc.) and industries to take action to serve themselves and their communities. Unlike the initially diffuse goals of the N.Z. National Science Challenge process, the MHW Taskforce approach would need to maintain focus on the operational goals and benefits. The choice of actions will depend on agility and risk appetite of the sectors. This will increase resilience in the short term to cope with longer term climate change, which in turn supports coastal communities. The overarching recommendation is a “taskforce” to champion and coordinate the response.

### Recommendation:

#### 12. *Development of a MHW Taskforce to have strategic oversight and coordination of science and societal outcomes (UNOD Societal Outcome A - Healthy and resilient ocean).*

There would be synergies with terrestrial heatwave applications and working groups, especially in the AoNZ setting. Such tools would nevertheless be central to bringing together decision-makers and stakeholders as well as act as a catalyst for inter-agency collaboration. It would provide a focal point for information for stakeholder and Māori groups.

Investment should focus on development of technical and operational capability and infrastructure for aspects like sustaining observational networks (Theme 3), computational capability in terms of serving forecast information. In addition,

investment will be required for workshops, pilot projects, social scientists, and environmental economists to collect information about impacts on coastal communities and quantify the value of forecasts to industry and communities. Capacity building will be vital because the increasing risk of damaging outcomes from MHWs will be such that we will need a strong cohort of people with skills and training in the interface between research, delivery, communications and emergency response. This capacity building is especially relevant for Māori communities, researchers and practitioners as they will be a key vector to support Māori interests (Theme 5). It is emerging that ocean warming and associated extreme events will have a serious and escalating impact on living near, and working in, AoNZ’s ocean environment. Maintaining societal systems into the Anthropocene will require development ahead of time of tools that can aid in the response and increase resilience to this challenge. This will save livelihoods and lives (IPCC, 2022).

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The mini-review was led by CSt and CSp with contributions to priorities and/or text from all other authors. All authors contributed to the article and approved the submitted version.

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