Marine Policy 88 (2018) 295–302

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

How can climate predictions improve sustainability of coastal fisheries in Pacific Small-Island Developing States?

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ABSTRACT

Climate and weather have profound effects on economies, the food security and livelihoods of communities throughout the Pacific Island region. These effects are particularly important for small-scale fisheries and occur, for example, through changes in sea surface temperature, primary productivity, ocean currents, rainfall patterns, and through cyclones. This variability has impacts over both short and long time scales. We differentiate climate predictions (the actual state of climate at a particular point in time) from climate projections (the average state of climate over long time scales). The ability to predict environmental conditions over the time scale of months to decades will assist governments and coastal communities to reduce the impacts of climatic variability and take advantage of opportunities. We explore the potential to make reliable climate predictions over time scales of six months to 10 years for use by policy makers, managers and communities. We also describe how climate predictions can be used to make decisions on short time scales that should be of direct benefit to sustainable management of small-scale fisheries, and to disaster risk reduction, in Small-Island Developing States in the Pacific

1. Introduction

Variability in weather and climate across spatial and temporal scales has a range of human and ecological impacts. Variability over long time scales (centennial and longer) has impacted viability of human civilizations [93] and redefined the distribution of major biomes [24]. At seasonal and interannual time scales, biomes, animal movements and human agricultural practices are influenced by climatic events [40], while daily and monthly variations in weather, including extreme events, also lead to dramatic impacts on people and environments [30,76,82]. These patterns of variability are superimposed on long-term, global climate change trends. Oceans are warming and altering environmental conditions in many regions, with impacts apparent across all sectors of the blue economy, from fishing to transport to energy generation [43,69].

The well-being of Pacific Island countries and territories (PICTs) is tightly linked to oceans and climate. PICTs can largely be thought of as small-island, large-ocean, developing states: combined, the area of their landmasses is only 2% of that of their exclusive economic zones (EEZs). Marine resources often provide the majority of income and protein for coastal communities [13]. A recent study estimates the production of Pacific Island coastal fisheries (i.e., those that harvest wild demersal fish and invertebrates from inshore coastal habitats and pelagic fish from nearshore waters for either commercial or subsistence purposes) to have been around 163,936 mt in 2014, worth approximately US$453 million [31]. Consumption rates of fresh fish among Pacific coastal communities are among the highest in the world, with average consumption in the majority of PICTs being 2–4 times the global average and with 50–90% of dietary animal protein in coastal, rural areas being derived from fish [12]. Coastal fisheries also provide many livelihoods across the region, with an average of 50% of surveyed coastal households in 17 PICTs receiving their first or second income from activities related to fishing [70].

Climate and weather have profound effects on economies, and the

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http://dx.doi.org/10.1016/j.marpol.2017.09.033
Received 28 March 2017; Received in revised form 22 September 2017; Accepted 25 September 2017

food security and livelihoods of communities, throughout the Pacific Island region [14]. Patterns of climate variability on the scale of days to years affect these communities in different ways. The most well-known oceanographic pattern affecting Pacific Island communities is the El Niño-Southern Oscillation (ENSO) [76]. Multi-month El Niño and La Niña events cause: (i) variation in the distribution, and hence regional catch, of tuna [54,55]; (ii) extensive coral bleaching events that reduce local fish abundance [46,72]; and (iii) influence the distribution of tropical cyclones, which can result in severe impacts to fish habitats and fishing infrastructure.

The ability to understand and anticipate changes in key climatic variables, e.g., sea surface temperature (SST) and circulation patterns, and predict weather events over the scale of months to decades offers immediate opportunities to governments and coastal communities to mitigate climate impacts and increase adaptive capacity. Development of models to forecast future climate states are developing quickly [61,64,75] and may allow predictive skill from six months out to a decade [9,60,80,81,91]. This will require the development of new approaches to designing and implementing climate adaptation policies, as management decisions respond to changing conditions over a range of time scales. Further, by taking advantage of the ability to mitigate, adapt and plan for change on inter-annual time scales, communities will be more able to respond to changes that occur over longer time scales [41].

In this paper, we outline the potential for climate predictions to support the adaptation and development of coastal fisheries in Small Island Developing States, focusing primarily on the Pacific Islands. We clarify the differences between climate prediction and projection, and which climate conditions might be skillfully predicted. We review documented examples of weather impacts on fisheries in the Pacific Islands region and identify how predictions could inform management. We then use this information to identify how predictions of climate variability can help forge policies to reduce the impacts of climatic variability on, and increase the adaptive capacity of, coastal fisheries.

2. Difference between prediction and projection

The terms ‘climate prediction’ and ‘climate projection’ are often confused as being the same. With regard to modelling the future, they are different activities with substantially different objectives. A *climate prediction* is aimed at describing the actual state of the climate system at a particular point in time, whereas a *climate projection* is aimed at describing the average or statistical properties of the climate system over a future time window.

For example, seasonal climate predictions attempt to forecast climate anomalies several months ahead, such as describing the actual state of large-scale modes of the climate system (e.g. La Niña conditions) or environmental conditions (e.g. surface temperatures) at a particular point in time. This is an initial-value problem that requires the climate model to start off in the same state as the real climate system and track the evolution of ENSO and other climate modes as they progress through particular phases. Initialization of the correct ENSO phase allows global climate prediction systems to forecast the evolution of tropical SSTs and the average weather over the next month or season. A climate projection, on the other hand, characterises the change in statistical properties of climate modes such as ENSO over a future period. A projection does not attempt to specify the ENSO phase at a given time, but rather whether one phase of ENSO will tend to be favoured more than another, or average temperatures, in a future timeframe, typically on the scale of decades and longer. Models used to make climate projections evolve in response to external forcing of the climate system (e.g., increasing CO_2). They do not need to be initialised to a particular ENSO phase when they start because they are not intended to track specific changes in that phase [75].

Skillful climate predictions may be extended to longer time scales than months by exploiting and focusing on slower processes in the climate system [61,64], such as the Pacific Decadal Oscillation (PDO). The basic principal is the same as weather forecasting – a longer-term climate prediction will be initialised to the current phase of the PDO and will attempt to track and predict the phase of the PDO. Climate projections by contrast, do not, and cannot, keep track of the particular phase of processes like the PDO [75].

3. Current understanding of climate variability and extremes in the Pacific

The heat content of the ocean is dynamic and SST varies on multiple temporal and spatial scales, with (for example) seasonal cycles being generally larger at higher latitudes (see [29]) for the Australian region). Although well studied, SST is not easily predicted and a notable source of uncertainty comes from the onset, severity and duration of ENSO [83]. Extreme and prolonged variations in SST unrelated to seasonal variations constitute events known as marine heatwaves [42]. The dominant driver of marine heatwaves in the subtropical and tropical Pacific Ocean is ENSO [83]. The Oscillation forces marine heatwaves in the central and eastern Pacific directly as an expression of El Niño and elsewhere either directly or indirectly through the processes that ENSO influences, including modified wind patterns and cloud coverage, which in turn impact air-sea heat fluxes.

Rainfall variability in tropical regions varies in conjunction with local convective processes and organised larger-scale convection in convergence zones. It is also influenced by the proximity to the tracks of tropical cyclones, which can deliver extreme rainfall in some years. Throughout the Pacific basin, variability of rainfall is strongly linked to the ENSO cycle, driven by shifts in the positions of large-scale convective zones. In the tropical Indian Ocean, precipitation is influenced by local monsoon circulations and by ENSO and the Indian Ocean Dipole (IOD).

Outside the tropics, variability in rainfall is set mainly by variations in atmospheric jet streams and storm tracks. These respond in part to tropical features such as ENSO and the IOD, but also to internal modulations and to changes in high latitudes that affect meridional temperature gradients in the atmosphere and the formation of genesis zones for storms. The Southern Annular Mode (SAM) represents north-south variations in the storm tracks, while the major blocking regions of the Southern Hemisphere [63] represent the east-west variation in storm track activity [74]. Both SAM and blocking high pressure systems modulate rainfall over the Southern Hemisphere extratropics.

Variability in rainfall is partly predictable on longer time scales when it relates to slower varying modes in the oceans and cryosphere [61]. For example, rainfall variations related to ENSO are partly predictable on time scales of months, whereas variations due to the PDO may have predictability spanning years [64]. These patterns are reflected in the large-scale spatial variations of upper ocean salinity, which integrates rainfall, thereby offering scope for enhanced predictability [65]. The controls of long-period variations in blocking and associated extreme rainfall events are still not well understood, but may also offer some scope for predicting rainfall [74].

The ENSO state offers some predictability of the frequency and potential location of cyclones in the southwest Pacific Ocean region [8,25,58,86]. During El Niño conditions, cyclones occur most frequently between Vanuatu and Fiji, and chances of occurrence are also high further east towards Samoa, southern Cook Islands and French Polynesia [52]. Under La Niña conditions, tropical cyclones are more frequent in the Coral Sea, and absent from Cook Islands eastwards [25].

4. Climate impacts on small-scale fisheries – case studies from the Pacific Islands region

4.1. Marine heatwaves

Marine heatwaves, defined as ‘a prolonged discrete anomalously warm water event that can be described by its duration, intensity, rate of evolution, and spatial extent' [42], can have devastating effects on coastal fisheries in Small Island Developing States. Impacts can occur in multiple ways, including: 1) through coral bleaching, resulting in reductions in quality and extent of critical habitat, 2) direct mortality of marine fauna through thermal stress, 3) indirect mortality of marine fauna through reductions in dissolved O_2 concentrations / increases in hypoxia in waters of elevated SST, and 4) avoidance of water bodies of elevated SST by mobile fish species, including nearshore pelagics [20,68]. These effects can result in long-term contraction or loss of fishing grounds, shifts in species distributions, and declines in local abundance, leading to depressed catch rates and declines in overall catches.

Coral bleaching events are a common feature of marine heatwaves in the tropical and subtropical Pacific, and are typically associated with strong El Nino phases [68,77]. The strong 1997/1998 El Niño caused bleaching in every ocean, resulting in 16% of corals being destroyed globally [44,45,88]. Severe bleaching was reported across much of the tropical and subtropical Pacific during the 2015/16 El Niño, including around the Cook Islands, Fiji, New Caledonia, Samoa, Tuvalu and Vanuatu. For example, in February 2016, a major coral bleaching event occurred along a 20 km stretch of the Coral Coast on the island of Viti Levu, Fiji. This event was caused by a severe, El Niño-induced marine heatwave, resulting in SSTs that were 2–3 °C higher than average in January, and a heat 'spike' over a five-day period in early February where SSTs peaked between 34–36 °C and failed to drop below 30 °C (Victor Bonito, Reef Explorer Fiji Ltd, pers. comm.).

Coral bleaching events can significantly alter the extent and quality of coral reef habitats and are particularly devastating for coral reef-dependent fisheries if coral recovery does not occur and regime shifts from coral-dominated systems to less desirable benthic assemblage types (e.g., algal turf or macroalgae) occur [47,71,72]. While studies have documented increases in the abundance of some functional groups of fish (e.g., herbivores) immediately after coral bleaching events [71], over longer time-fames most reef-associated fish are expected to be less abundant in habitats with low coral cover due to declines in the structural complexity of reefs [35,72].

Marine heatwaves can also lead to direct or indirect fish mortality in both coastal and nearshore waters. For example, the 2016 bleaching event on the Coral Coast of Fiji described above was accompanied by a major fish kill - thousands of fish and invertebrates died, presumably from low dissolved O_2 concentrations in the superheated water column (V. Bonito, pers. comm.). Similarly, the occurrence of a long period of unseasonably warm, still weather was considered to be a significant factor driving a large phytoplankton bloom – which ultimately led to declines in dissolved O_2 and the death of thousands of marine fauna in a large ($> 20\ km^2$) embayment in the Western Province of the Solomon Islands (Simon Albert, University of Queensland, pers. Comm, [1]). This event caused health complications amongst community members who consumed dead fish and invertebrates, including dizziness, diarrhea, aches and weakness, (S. Albert, pers. comm.), and resulted in a shift from a coral-dominated to a cyanobacteria-dominated system [1]. Such changes in benthic cover have significant negative long-term impacts on local communities because cyanobacteria-dominated systems do not support as many fish as coral-dominated systems [1,62].

Marine heatwaves can also significantly affect the distribution of pelagic species, reducing their availability for small-scale fishers. Climate cycles such as ENSO are key drivers of variation in the distribution of tuna and the location of tuna catches in the Pacific Island region. Under strong El Niño conditions, industrial fishing for skipjack tuna is generally displaced further eastward along the equator and at higher latitudes - catches decline in western PICTs, such as Papua New Guinea, Federated States of Micronesia and Solomon Islands, and increase in Kiribati [54,55]. The shallowing of the thermocline in the western Pacific during El Niño events constrains the vertical habitat of yellowfin tuna, resulting in higher catch rates of this species by the surface fishery in the warm pool [54,55].

4.2. Tropical cyclones and severe storms

Tropical cyclones and severe storms can have significant effects on fish stocks, their supporting habitats, fishing fleets and fisheries yields and, consequently, protein intake and sources of livelihood for dependent communities. Tropical cyclones directly impact coral reefs, mangroves, seagrasses and intertidal areas through physical damage, resuspension of sediments, pulses of nutrient enrichment and freshwater inundation, altering their extent, structural complexity and benefit as fish habitats [37,39,46,85,90], with subsequent effects on local fisheries [72]. Changes in fish species density and biomass, and catch rates of target species, are common after such events [23,56,79,84,89]. For example, significant decreases have been reported [84] in fish species richness, density and biomass on reefs in southern New Caledonia following Cyclone Erica, a Category 5 tropical cyclone (TC). Such changes can result in reductions or loss of critical ecosystem functions, leading to regime shifts to less desirable benthic assemblage types (e.g., from structurally complex coral-dominated systems to rubble-, turf- or macro-algal-dominance) [23,84]. In addition, increased runoff resulting from extreme rainfall during cyclones or stand-alone heavy rainfall events can add to the physical destruction of coral and seagrass habitats caused by storm surge [46,89]. Prolonged turbid conditions reduce the light needed by the symbiotic dinoflagellates that provide much of the food for corals, and needed by seagrasses for growth. In addition, the higher nutrient loads associated with increased runoff cause problems for coral reefs by stimulating the growth of epiphytic algae, which also reduces light levels for corals. The time required for reefs to recover from disturbances, including cyclones and coral bleaching, can temporally increase suitable habitat for ciguatera-causing dinoflagellates, resulting in increased incidence of ciguatera fish poisoning [72,73].

Tropical cyclones and severe storms have direct economic implications for coastal fisheries and aquaculture in small island states by reducing fishing time and destroying or damaging fishery assets and infrastructure, such as landing sites, boats and equipment [5,26]. For example, in Vanuatu, the estimated physical damage to the fisheries sector following the Category 5 TC Pam in 2015 was valued at VT 268 million (~USD$2.6 million), with half of the damage affecting artisanal fisheries, and the other half distributed between commercial fisheries (24%), loss of fisheries infrastructure (17%), community aquaculture (5%), fisheries market facilities (3%) and subsistence fisheries (1%) [34]. Similarly, the estimated physical damage to wild-capture, coastal fisheries after TC Winston, an extremely destructive Category 5 cyclone that struck Fiji in February 2016, was valued at F$33 million (~USD $16 million), with coastal subsistence fisheries sustaining the majority of damage (F$27.7 million) [32]. In Samoa, an estimated 27% of canoes owned by artisanal fishers were damaged during TC Evan in December 2012, while it was estimated that artisanal fishers would experience a loss of fishing income for two months [33].

5. Climate variability prediction skill across different time scales

Seasonal to inter-annual prediction has been applied, with moderate success, to generate predictions of the climate state (e.g., ENSO phase) [6,57] and the potential impacts from changes in climate state (e.g., rainfall probabilities) and/or tropical cyclone activity [21,51] across the globe. In particular, recent developments in our understanding of the processes underpinning ENSO, improvements in model resolution and parameterisations, and observing and analysis/assimilation systems, are seen as important in improving ENSO predictions [38]. In the 1990s, real-time ENSO prediction capability was moderate, with 6-month lead predictions (hindcasts) of 3-month mean SST conditions being correlated at about $r = 0.6$ with observations [7]. At the time, dynamical models were viewed as not performing any better than statistical models, e.g., predictions of the 1997/98 El Niño [6,53].

Nevertheless, ENSO predictability has gradually improved, and prediction skill from dynamical models has now exceeded analogous skill from statistical models [7]. However, inter-seasonal prediction systems continue to face challenges, for example, the predicted strong El Niño event for 2014/15 did not eventuate [59]. Ultimately, improved predictability of ENSO and its impacts will require better understanding of the diversity of ENSO patterns and their time evolution [22].

On sub-seasonal time scales, a major source of predictability in the climate system, particularly in the tropics, resides in the Madden-Julian Oscillation (MJO). The MJO is the dominant mode of intra-seasonal variability (approx. 30–90 days) in the tropical atmosphere. The MJO influences ocean variability in the Indo-Pacific region through changes in tropical cyclone activity [50], sea level [66], ocean currents [48], SST [28] and primary productivity [49]. The MJO can be predicted on time scales of 2–4 weeks [67], providing enhanced skill for long-range predictions that bridge the gap between weather forecasts and seasonal climate predictions [92]. There are numerous potential applications for skillful forecasts on subseasonal-to-seasonal (S2S) time scales [87]. However, our knowledge of the potential for S2S applications to ocean temperatures and fisheries is in its infancy.

Skill for climate predictions on all time scales is still very moderate, due to the infancy of forecast work and due to the inherent limitations of making forecasts over longer time scales [60]. On seasonal to multiyear scales, predictions for temperature are already better than using climatological estimates because of the persistence of ENSO and its impact on temperature in different regions. Seasonal to multiyear predictions of rainfall are currently of very low skill (not much better, if at all, than climatology), but offer scope for improvement where the ENSO signal is strongest [60]. One advantage for fisheries applications is that skill will generally be higher for the ocean than for the atmosphere and land because the processes responsible for multiyear predictability are in the ocean [61].

Traditionally, climate forecasts have focused on seasonal time scales and have exploited the persistence of ENSO events. Extending climate forecasts to multiyear and decadal time scales is a newer development that has been enabled by the availability of a longer record of subsurface ocean data, where processes reside for longer time scales. At this stage, it is still unclear how much predictability exists on multiyear time scales, but this will depend in part on how well slower processes like the Pacific Decadal Oscillation (PDO) can be forecast [64]. Climate models initialised to the current phase of the PDO already display some skill for multiyear temperature forecasts [60].

6. Application of climate predictions to policy and management

6.1. Implications for Pacific Island governments and communities

Our understanding of the patterns of variability and impact suggest that the most important current gap for climate predictions to respond to the impacts listed in Section 4 is between 6 months and 10 years. Predictions over that timeframe will enable more proactive mitigation, adaptation and avoidance by governments and communities on shorter timescales than are currently possible. For example, there would be the potential better to mitigate impacts on small-scale fishers and coastal community infrastructure, to stockpile resources at the most appropriate times when cyclones can be predicted at longer time scales, or to alter fishing patterns in anticipation of climate-induced movements or mortality events in future years. We highlight three specific events that predictions will be able to highlight: a) Increased El Niño-like conditions; b) Short- to medium-term (on the scale of months to years) marine heatwaves; and c) Increased severity of cyclones and storms.

Several opportunities exist to assist Pacific Island governments, small scale fishers and communities to adapt to the effects of shorter-term and mid-range climatic variability by extending regional and national predicting capability. Many of these interventions, which are outlined below and summarised in Table 1, are not new. They have been proposed for many years as an integral part of effective coastal zone management [4,27] and for mitigating longer-term effects of climate change on fisheries and aquaculture in PICTs [14,15,17]. Following [17], our identification of adaptation options included consideration of potential social and financial barriers to the uptake of adaptations, such as cultural norms and gender issues that could limit broad-based community participation, rather than being based solely on the availability of technology and projected future responses of the resources underpinning coastal fisheries production.

In addition, we focus on adaptation mechanisms that promote greater resilience of coastal ecosystems and small-scale coastal fisheries to the longer-term impacts of climate change (i.e., adaptations under the 'win-win' and 'lose-win' scenarios of [17]. We specifically excluded 'win-lose' investments, such as support to increase coastal fishing effort or capacity through construction of larger vessels or more effective gear types [17], because they represent maladaptation to the longer-terms effects of climate change for small-scale coastal fisheries.

6.2. Predictions to assist adaptations for coastal fisheries

A prime example of adaptation to assist small-scale fishers catch more fish on a day to day basis to help feed rapidly-growing populations would be to develop effective tools for predicting when yellowfin and skipjack tuna, and other associated large pelagic fish like wahoo and mahi mahi, are likely to be available in good numbers in nearshore waters [18]. When combined with programs to expand the number of nearshore fish aggregating devices (FADs) [16], which will require installation and maintenance of FAD infrastructure [16] and training in safe and effective FAD-fishing methods [18], effective prediction tools will assist communities to schedule their various other livelihood activities and adaptations to climatic variability and climate change, e.g., production of subsistence food crops [10,78]. Governments might also provide supports for alternative livelihood programs and set up social safety nets or insurance programs for small-scale fishers and communities [3]. Better predictions of tuna abundance should also confer benefits on industrial tuna fisheries in the region (see Supplementary Material).

Being able to extend predictions regarding extremes, such as marine heatwaves and tropical cyclones, will justify disaster preparedness programs and enable better decision making on the part of coastal fishers, communities and governments, potentially leading to faster recovery of affected ecosystems. For example, it will allow communities to be notified in advance of the risks to public health associated with 1) eating dead and decaying fish that wash up on beaches following fish kills, or 2) fish harvested from reefs that are likely to have a higher incidence of ciguatera fish poisoning. Predictions will also allow plans to be made to transfer fishing effort away from coral reefs predicted to be affected to nearshore pelagic fish, or from reef fish species worst affected by extreme weather events to species that typically increase in local abundance following such events. Such predictions will help to 1) maintain the overall catch of fish, and 2) promote restoration of the ecological function of coral reefs. However, caution will be needed to limit harvests of fish species that have important ecological functions, e.g., herbivores [19], or have an inherent vulnerability to overfishing [36]. Similarly, planned harvests of ecologically important invertebrates, such as sea cucumbers, trochus or giant clams, could be postponed to allow these groups to perform their key ecological functions.

Predicting climatic extremes, such as cyclones or marine heatwaves, well in advance may also allow sufficient time to mobilise available resources and stockpile fish and food products to support coastal communities to endure these difficult events and to mitigate their impacts afterwards. Specific actions might include, for example, accumulating alternate fish protein resources with a longer shelf life (e.g., canned tuna, smoked and dried fish), or placing fish in cold storage prior to a natural disaster and to reduce fishing pressure on affected

Table 1
Summary of potential management and policy adaptation options for coastal fisheries in small-island developing states under various climate prediction scenarios.

Event	Impacts	Adaptation options	Supporting policies
Increasing El Niño-like conditions	Movement of tuna eastward along the equator and at higher latitudes, with declines in catches occurring in western PICTs.	Installation / maintenance of fish aggregating devices (FADs), especially to help aggregate available tuna closer to coastal populations in western PICTs, including fisheries agency budget planning to ensure funds are available for maintenance and repair of FADs.	Include nearshore FADs as part of the national infrastructure for food security. Transfer some access rights and allocations from industrial tuna fisheries to small-scale fisheries.
		Flexible arrangements to allocate more of the tuna resources to local food security.	Apply targeted subsidy and training programs to support key adaptations.
		Increase allocation of area of the EEZ available to small-scale fishers	Collaborative monitoring and decision-making processes to ensure that proposed interventions are appropriate and effective
		Improved post-harvest methods and food storage systems to stockpile tuna and small pelagics when good catches are made.	
		Implementation of alternative livelihood programs for small-scale coastal communities	
		Creation of social safety nets – e.g., insurance programs for SSF, community insurance banks - for communities.	
Short-medium term marine heatwaves	Fish kills under persistently warmer conditions (e.g. due to low dissolved O_2)	Awareness raising to avoid health implications of eating dead and decaying fish, and fish with ciguatera poisoning.	Strengthen fisheries legislation to apply community-based management.
	Coral bleaching and subsequent overgrowth by macroalgae and increase in ciguatoxic microalgae.	Awareness raising of event, likely impacts, and importance of herbivorous fish in facilitating reef resilience and recovery.	Promote access to nearshore pelagics such as tuna and fish expected to increase in abundance; include nearshore FADs as part of the national infrastructure for food security.
		Flexible management practices to allow establishment of temporary 'no-take' areas or gear restrictions (e.g., bans on night spearfishing with torches).	
	Changes in fish community composition and species' abundance.	Installation / maintenance of FADs to aggregate tuna and other small pelagics near coastal communities.	Apply targeted subsidy and training programs to support key adaptations.
	Declines in extent and quality of habitats and loss/contraction of fishing grounds.	Fuel and gear subsidies to encourage fishers to fish on FADs to transfer fishing effort away from reefs.	Collaborative monitoring and decision-making processes to ensure that proposed interventions are appropriate and effective
	Depressed catch rates and declines in overall catches of key target species.	Flexible arrangements to allocate more of the tuna resources to local food security.	
		Improved post-harvest methods and food storage systems to stockpile tuna and small pelagics when good catches are made	
Increased severity of cyclones and storms	Declines in extent and quality of habitats and loss/contraction of fishing grounds	Awareness raising to avoid health implications of eating fish with ciguatera poisoning.	Strengthen fisheries legislation to apply community-based management.
	Overgrowth of dead coral by macroalgae and increase in ciguatoxic microalgae.	Awareness raising of event, likely impacts, and importance of maintaining stocks of herbivorous fish in facilitating reef resilience and recovery.	Promote access to nearshore pelagics such as tuna and fish expected to increase in abundance; include nearshore FADs as part of the national infrastructure for food security.
	Changes in fish community composition and species' abundance.	Flexible management practices to allow establishment of temporary 'no-take' areas or gear restrictions (e.g., bans on night spearfishing with torches).	Apply targeted subsidy and training programs to support emergency preparedness and key adaptations.
		Installation /maintenance of FADs to aggregate tuna and other small pelagics near coastal communities.	
	Depressed catch rates and declines in overall catches of key target species.	Fuel and gear subsidies to encourage fishers to fish on FADs to transfer fishing effort away from reefs.	Collaborative monitoring and decision-making processes to ensure that proposed interventions are appropriate and effective.
		Flexible arrangements to allocate more of the tuna resources to local food security.	
	Damage to fishing fleet.	Improved post-harvest methods and food storage systems to stockpile tuna and small pelagics when good catches are made.	
		Flexible licensing provisions (where relevant) and gear subsidies to allow fishers to target other species/areas.	
		Emergency preparedness training programs in coastal communities and early warning systems to ensure preparedness (e.g., move fleet, secure gear).	

reefs in the weeks to months following the event. In the lead-up to a predicted event, coordination of increased fishing on FADs at a local scale, or increased landings of tuna by industrial fleets for domestic food security at a national scale, may be required. In either case, investment in storage facilities may be required. Predicting destructive weather and climate events over extended time scales may also provide sufficient warning to move vessels onto land above the reach of storm surges, and secure vessels and other community infrastructure against wind damage. Similarly, loss of fishing gear could be minimized if sufficient time is provided to retrieve and securely store the equipment before the onset of a cyclone. The widespread use of mobile phones throughout PICTs now provides the opportunity for government agencies involved in disaster risk management to issue bulletins alerting small-scale fishers to impending risks with sufficient notice to enable to them to store boats and fishing gear in cyclone-proof storage [18]. It is not practical to use predictions of adverse weather condition to climate-proof FADs by removing them from the water in the lead-up to storm events due to the difficulties in doing so from small craft. Instead, spare FADs materials can also be stored in cyclone-proof containers on each island and installed once the storm has abated (Bell et al. this volume b). Reliable predictions will enable PICTs to plan annual budgets to ensure funds are available for FAD maintenance and repair (Table 1).

Predictions over intermediate time scales may also allow communities to adopt flexible management measures, including temporary fishing closures on areas predicted to be worst-affected, appropriate size limits, regulations on fishing gear and bans on certain fishing methods (such as night-time spearfishing with torches), prior to and following the event to reduce fishing pressure on coastal habitats and vulnerable fish species. Such measures should help to maintain and promote reef resilience and recovery. On the other hand, the combination of predictions and monitoring of species movements might also allow communities to take advantage of emerging stocks and resources. Strengthening the role of collaborative governance and community-based management will be a vital part of this process [2]. Some PICTs have invested in aquaculture technology to culture species such as giant clams and sea cucumbers (in particular sandfish, *Holothuria scabra*) to help restore wild stocks [11]. Extending climate prediction over the scale of six months to 10 years would inform operations of optimal times for release of cultured juveniles, and what remedial action to take to counter or avoid poor conditions. Improved climate predictions would also be of benefit to the aquaculture industry (Supplementary Materials).

6.3. Communication of climate predictions

Effective communication is critical to the application of climate predictions. This is particularly challenging in the geographically and culturally diverse Pacific Island region. Communication strategies should focus on: (1) targeting the most vulnerable stakeholders, and (2) delivering predictions in a way that is easily understood and directly relevant to their needs. Based on our current understanding, this implies that predictions will be needed on time scales of six months, 1, 2, 5 and 10 years. Communities and governments across the Pacific islands region are reasonably well informed about the concepts of climatic variability and climate change, but often receive limited information to inform their understanding of the implications beyond the effects of long-term sea-level rise due to climate change. Using the developing infrastructure for connectivity based on mobile phones will allow for wider and more rapid dissemination of information. However, it will require care to ensure that the applications developed for mobile phones are conveying information suitable for uptake by a range of users.

Much of the information needed to develop predictions of the occurrence and abundance of tuna and other large pelagic fish in the coastal waters of PICTs is now available in open-access, global databases [18]. The main tasks are to: synthesise this information to identify periods when the conditions preferred by these fish species are likely to occur weeks, months and years in advance by combining existing seasonal predictions with longer term predictions; validate the reliability of predictions; and develop practical systems for disseminating predictions to small-scale fishers.

Communication should also not be seen as unidirectional – participatory monitoring of oceanic, climatic and fisheries conditions can be used to corroborate predictions and deliberations should be undertaken between governments and stakeholders to develop locally appropriate and effective responses. A promising way to validate the predicting tools will be to collaborate with a group of communities to attach acoustic buoys to a subset of FADs, transmit the information on associated fish biomass to the relevant national agency, and correlate the acoustic data on fish biomass with predictions of conditions preferred by tuna and other large pelagic fish.

7. Conclusion

The utility of climate predictions will depend on the skill of the prediction and on the ability of local community decision-making, sectoral planning, or national policy responses to plan over intermediate time scales of six months to 10 years. Over shorter time periods, there are a number of options for adaption (outlined in [17]). In the six month to 10 years' time period, improving an understanding of frequency, trend and location of events are critical areas for research, but many decisions are not so "sophisticated" that a specific temperature threshold is needed. This timeframe corresponds neatly with the planning horizons for many development activities. The availability of climate projections has raised awareness of the need to take long-term action to limit the magnitude and impacts of greenhouse gas emissions, but tactical decision-making about investments over these intermediate time scales remains limited. Improved prediction of climatic variability will help address this situation and allow both policy makers and fishers to adapt to climate events. However, to harness the potential benefits of improved predictions, stakeholders in coastal fisheries will need to become more flexible. In particular, policy and management responses will need to vary over the same time scales as climatic variability. In many Pacific Island countries, support will be needed to make this transition.

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.marpol.2017.09.033.

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