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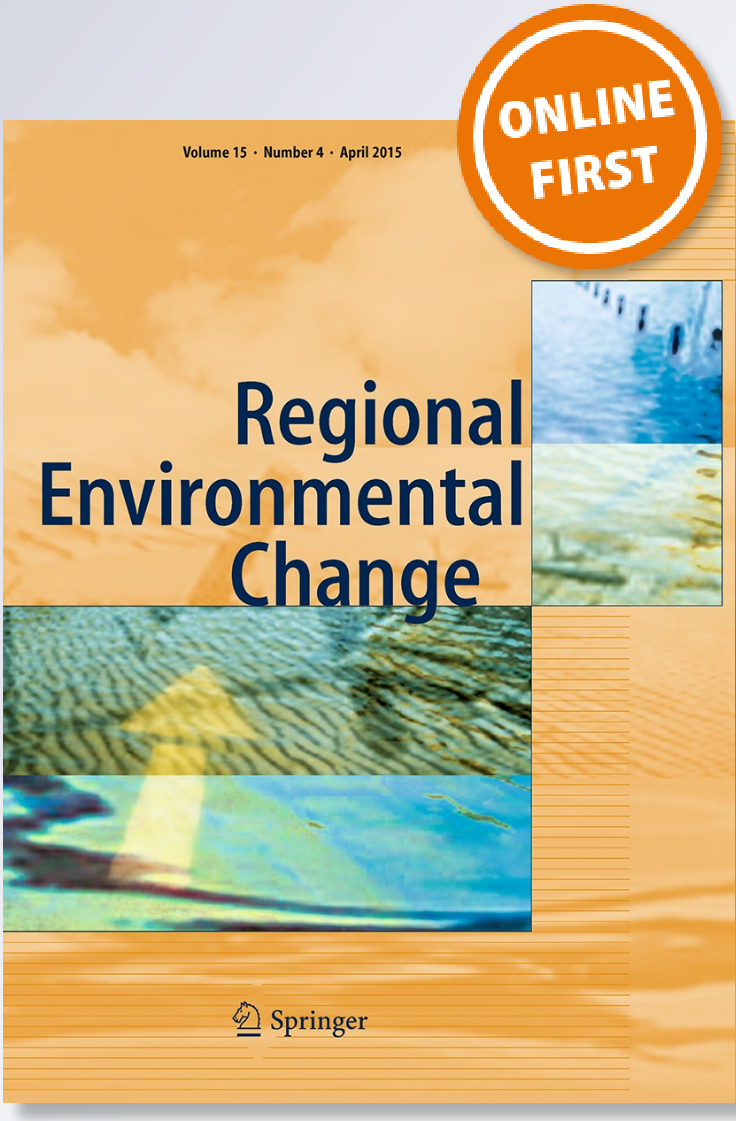

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ORIGINAL ARTICLE

Integrating social–ecological vulnerability assessments with climate forecasts to improve local climate adaptation planning for coral reef fisheries in Papua New Guinea

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Abstract A major gap exists in integrating climate projections and social–ecological vulnerability analyses at scales that matter, which has affected local-scale adaptation planning and actions to date. We address this gap by providing a novel methodology that integrates information on: (i) the expected future climate, including climate-related extreme events, at the village level; (ii) an ecological assessment of the impacts of these climate forecasts on coral reefs; and (iii) the social adaptive capacity of the artisanal fishers, to create an integrated vulnerability assessment on coastal communities in five villages in Papua New Guinea. We show that, despite relatively proximate geographies, there are substantial differences in both the predicted extreme rainfall and temperature events and the social adaptive capacity among the five fishing-dependent communities, meaning that they have likely different vulnerabilities to future climate change. Our methodology shows that it is possible to capture social information and integrate this with climate and ecological modeling in ways that are best suited to address the impacts of climate-mediated environmental changes currently underway across different scales.

Keywords Climate change · Adaptation planning · Socioecological vulnerability · Coral reef fisheries · Papua New Guinea

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Introduction

Human activities are changing the climate system with significant repercussions for all life on Earth (IPCC 2007; Grimm et al. 2013). It is now thought that the planet has warmed about 0.74 °C over the last century (Stocker et al. 2013), and social and ecological impacts of this warming are now evident, as reflected in the increasing threats to livelihoods, assets and security experienced by coastal communities in the tropical regions worldwide (Nelson et al. 2007; Allison et al. 2009). Unprecedented climates are projected to occur earliest in the tropics and among low-income countries, highlighting the vulnerability of global biodiversity and the limited governmental capacity to respond to the impacts of climate change (Mora et al. 2013; Stocker et al. 2013). Without aggressive greenhouse gas emissions mitigation policies being implemented in the short term, global mean temperatures are projected to further increase by 1.1–6.4 °C by 2100 (Stocker et al.

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2013), which will have serious ramifications for social and ecological systems across the tropics. Consequently, policy makers and natural resource managers are seeking ways to effectively prepare for and respond to the consequences of environmental changes via linked social–ecological vulnerability assessments (Turner et al. 2003; McClanahan et al. 2008; Rands et al. 2010; Cinner et al. 2013).

To date, most assessments of the vulnerability of tropical coastal regions to climate change impacts—and the management and policy recommendations that come from them—have been conducted at global, regional, and national scales (e.g., Allison et al. 2009; Watson et al. 2013). These broad-scale studies are important for international comparisons, as well as for identifying the relative importance of impacts and potential adaptations within particular sectors (O'Brien et al. 2004). However, broad-scale studies are usually deficient of detailed information that is necessary for appropriate adaptation planning at the scales where management actions need to be conducted, such as community and village scales (Cinner et al. 2013; Mamauag et al. 2013).

The few coastal vulnerability assessments that have been focused at the community scale have been able to incorporate local-scale adaptation issues unavailable in larger-scale assessments, such as traditional knowledge and existing coping practices (e.g., Dolan and Walker 2006; Cinner et al. 2012). While these studies have demonstrated how community-scale coastal vulnerability assessments can inform adaptation planning, to date, none have incorporated projections about likely future exposure to climate change (in particular, extreme events, e.g., droughts and floods) into their assessments. This is generally because the resolution of the climate forecasts is too coarse to capture the processes that dominate the coastal and shelf regions. In this study, we address this issue by using better-resolved historical satellite data together with future projections to estimate future exposure to extreme events relative to historical baselines. We undertake this at two spatial scales: national scale using climate model projections of air temperature and rainfall and village scale using historical satellite-derived sea surface temperature data together with future projections.

Most operationalized conceptual frameworks of social–ecological vulnerability provide analyses that are inclusive of the key socioeconomic and environmental indicators in a coupled social–environment system (e.g., Allison et al. 2009; Cinner et al. 2013). Indicators are often grouped into three dimensions of vulnerability, i.e., sensitivity, adaptive capacity, and exposure (e.g., Adger 2006; Allison et al. 2009; Cinner et al. 2012). Consequently, models of vulnerability assessment consider the interrelationship between social and environmental indicators, and the functional relationship between vulnerability dimensions, such that sensitivity and exposure reinforce vulnerability, while the adaptive capacity counteracts or balances vulnerability (Turner et al. 2003; Adger 2006). In this conceptual framework, our study operationalizes the exposure and adaptive capacity dimensions of vulnerability (e.g., McClanahan et al. 2008) and subsequently assesses relative positions of the coastal communities in this vulnerability space.

We focus on fisher communities because, like in most sectors, the impacts on fisheries are scale-dependent and are unevenly distributed within regions, countries, communities, and individuals as a result of differential exposures and vulnerabilities (Clark et al. 1998; Cinner et al. 2013). Using fisher communities on Manus Island (Papua New Guinea) as a case study, we demonstrate that a process that integrates social adaptive capacity of a fisher village, the exposure of coral reefs to environmental perturbations, and the future extreme climate is not only possible, but also allows for a more holistic assessment of how vulnerability to climatic change to date changes among villages. Our findings can be used by decision makers to rapidly identify different adaptation options that are suitable in both the near and the far term, and this methodology can be replicated by natural resource managers at a scale essential for local implementation.

Methods

Study area

Papua New Guinea (PNG), the largest developing country in the South Pacific, is designated as both a low-income food deficit and a least developed country (LDC) based on low levels of income, skill capacity, and food security (FAO 2000; Kronen et al. 2010). The physical, social, and economic characteristics of PNG make it highly vulnerable to the foreseen intensification of storm surges, cyclones, and rise in sea levels (Church et al. 2006). In particular, coral reef fisheries, which is a food security mainstay in PNG and in Melanesia region as a whole, have declined over the past five decades and could further decrease by 20 % by 2050 (Bell et al. 2013). Papua New Guinea is therefore an important case for understanding the context, strategies, and capacities in response to climate change, particularly with regard to social–ecological climate change vulnerability.

Communities in five villages in Manus province were targeted for survey research on the basis of their dependence on coral reef-based activities as the main source of livelihood and based on the fieldwork logistics. These villages included four on the north coast of Manus (Ponam, Andra, Lahapau, and Tulu) and Pelipowai on the south coast of Manus. Two of these villages (Ponam and Andra) are home to island communities that are heavily dependent on marine resources for their livelihoods (Cinner 2005; Cinner et al. 2005). In these island communities, marine resources are governed by complex customary tenure arrangements that determine where specific families and clans can fish, the types of gears they can use, and even the species they can target, which have been described in detail in several in-depth studies (Cinner 2005; Cinner et al. 2005; Carrier 1982; Carrier and Carrier 1983). Ownership of marine resources primarily (but not exclusively) rests with the island, versus the mainland communities. Alternatively, ownership of terrestrial resources, such as timber, rests with the mainland communities. During the Northwest monsoon season (November to March), sea surge, coastal flooding, high salinity, and coastal erosion are common on the mainland coastal villages, and to a larger extent on the islands. Consequently, extreme weather impedes fishing activities, one of the main livelihood activities for the island communities. Moreover, transportation of food and basic needs from the mainland is difficult during extreme weather, which can lead to food shortages on the islands. More information can be found in online resource 2.

Environmental exposure

Climate variables influence coral reef social–ecological systems through a range of direct and indirect pathways (Allison et al. 2009). Here, we considered exposure pathways to include the physical exposure as represented by temperature and precipitation extremes events and the ecological exposure as represented by exposure of coral reefs to climate-related disturbances, also described in the following sections.

Exposure to extreme climatic events

Temperature and rainfall extreme events may influence fisheries indirectly by, among others, limiting activities associated with fisheries (for example, floods associated with extreme precipitation might affect access to fishing grounds and markets), while extreme temperature may influence corals and fish physiology, sex ratios, production, and the timing of migrations and spawning (Munday et al. 2008). Consequently, understanding the nature of potential changes in the probability of extreme temperature and rainfall events in the context of global warming is important for the assessment of human population and ecosystem consequences (Christensen et al. 2007).

National-scale climate exposure To analyze changes in the frequency of extreme climate and weather events relative to baselines in PNG, we used a published database of historical and future climate indices computed using a consistent methodology across different modeled and observational data by the Expert Team on Climate Change Detection and Indices (ETCCDI) (Zhang et al. 2011). ETCCDI has defined 21 indices that represent extreme events of temperature and rainfall, as part of the efforts to facilitate the understanding of the observed and projected climate change (Sillmann et al. 2013a, b). Among these, we selected three rainfalls and three air temperature indices that represent extreme conditions (Online resource 1). These included percentile-based indices, which represent the exceedance in rates (%) above the 90 and 99 % (R99p) of temperature (TX90p) and rainfall distribution, respectively, derived from a base period of 1961–1990. The very heavy precipitation days index (R20 mm) counts the number of days with more than 20 mm of rainfall in a given year. The warm spell duration index (WSDI) counts the number of days in a year when daily maximum temperature is above the 90th percentile for six consecutive days or longer. WSDI is based on the percentile thresholds calculated from the base period 1961–1990 (Sillmann et al. 2013a). The consecutive dry day index (CDD) represents the length of the longest period of consecutive dry days (i.e., days with rainfall <1 mm) in a year ending in that year. CDD describes the lower tail of the rainfall distribution and is often used as an indicator for drought. TXX represents the absolute annual maximum of the daily maximum temperature. Detailed information on the indices can be found in Alexander et al. (2006), Zhang et al. (2011) and on the ETCCDI website (http://www.cccma.ec.gc.ca/data/climdex/climdex.shtml). We downloaded data for the six indices computed from future temperature and rainfall projected using the latest suite of IPCC AR5 models participating in CMIP5 and for historical, and the most optimistic scenario (RCP 26) (Moss et al. 2010; Taylor et al. 2012). For each of the six extreme indices, we extracted time series data for all pixels spatially overlapping PNG and obtained an average of the time series.

Village-scale climate exposure To conduct village-level analysis of extreme events, we integrated relatively high-resolution satellite-derived satellite SST data ($\sim$4 km $\times$ 4 km grid) with GCM data (typically 1°–2° grid) and analyzed for the frequency of exceedance of a fixed threshold in sea surface temperature (SST) time series relative to a baseline period. We used a well-established definition of the extreme event threshold, previously defined as the 99th percentile of the baseline SST distribution (i.e., occurs on less than 1 % of months) (Barnett et al. 2006). Twenty year monthly time series (1985–2005) SST NOAA satellite observations were used as the baseline period. To achieve this, future SST projections based on

RCP scenarios and 5 different model families were obtained from the CMIP5 archives (http://cmip-pcmdi.llnl.gov/cmip5/data_portal.html). Monthly time series for each model family and scenario were grouped into four 20-year intervals (i.e., 2010–2029, 2030–2049, 2050–2069, and 2070–2089). For each village, model family, scenario forcing (RCP's 2.6, 4.5, 60, and 8.5) and time series interval, relative frequency of extreme events (RFEE) was calculated as the proportion of future monthly SST over the 20-year period that exceeds the threshold of the historical SST distribution (i.e., a baseline period of 1985–2005).

Coral reef ecological exposure

To represent the ecological disturbance pathway, we utilized an existing coral reef multivariate exposure model (Maina et al. 2011), which was constructed using satellite sea surface temperature-derived metrics (i.e., temperature variability, long-term maximum and minimum, and temperature skewness), UV light, wind speed, coastal suspended sediments, and chlorophyll data to estimate the exposure of coral reefs globally (see Maina et al. 2011 for a detailed description). Outputs from this model are gradients between [0,1], representing no exposure and severe coral reef exposure to, respectively. The spatial resolution of the data used in the model ranged from 4.5 × 4.5 km to 50 km × 50 km; therefore, the spatial variability in exposure can be evaluated for locations that are > ~4 km apart (Maina et al. 2011). Exposure indices were extracted from the multivariate exposure model for the marine points adjacent to the five villages.

Assessing the social adaptive capacity of each village

Questionnaires designed to elicit qualitative and quantitative information on indicators of adaptive capacity were administered to 126 fishermen from five villages in Manus province (Online resource 3) (i.e., Andra = 25; Lahapau = 15; Pelipowai = 9; Ponam = 45; and Tulu = 32). The semi-structured interviews were conducted in Tok Pisin language and responses translated to English. In two island villages (i.e., Ponam and Andra), systematic sampling was used where every third person on the list of fishermen provided by the respective village community leaders was chosen for interviewing. If the selected person was not available, the next person on the list was chosen. In villages with relatively small fisher population (i.e., Tulu, Pelipowai, and Lahapau), all available fishermen were interviewed.

It is generally agreed that social adaptive capacity confers the ability to recover from stressful events and conditions and to take advantage of the opportunities provided by change (Adger 2006). In our study, social adaptive capacity indicators were selected deductively on the basis of theoretical understanding of adaptive capacity and the interrelationships among indicators. Consequently, the study conceptualizes social adaptive capacity as a composite of 16 social indicators, subsequently enumerated as (a–q) and conceptually grouped into six key dimensions, following extensive engagement with relevant literature sources (including Adger 2006; Folke et al. 2005; Bodin and Crona 2008; Kithiia 2010; Cinner et al. 2012, 2013). The six dimensions are outlined below and interpreted in Online resource 4.

(I) Situation awareness—broadly defined as having the right information at the right time to make the right decisions (Rauwolf et al. 2013). Situation awareness, which includes comprehension, perceptual processing, and causative predictions, is a foundational skill in generating useful human action selection mechanisms (Rauwolf et al. 2013). We looked at three indicators on situation awareness: (a) whether fishers recognized declining trends in the fishery status, (b) whether they could attribute decline to a range of causal factors, and (c) whether they could identify mechanisms for reversing decline.

(II) Climate change risk perceptions—climate risk perceptions determine how communities are predisposed to taking mitigative actions, and their level of preparedness in anticipation of the perceived risks (Brunckhorst et al. 2011). To assess the climate change risk perceptions, we considered three indicators: (d) whether climate and weather-related risks are major considerations for the community, (e) climate risks being addressed, and (f) perceptions on who/what is at risk.

(III) Current adaptation options—measures, initiatives, strategies, or activities that are being undertaken to address climate change impacts on fisheries (Kliver 2008). We looked at three indicators of current adaptation options: (g) current initiatives for reducing climate change-mediated impacts on fisheries, (h) the number of entities or groups involved, and (i) alternative livelihood activities.

(IV) Role of non-state actors—these are fisheries stakeholders that do not have a legal status as a state or agent of a state, working at various levels to address the impacts of climate change. These may include NGOs, private businesses, voluntary interest groups, faith-based organizations, expert/scientific communities, and village committees. We looked at four indicators of the role of non-state actors (j) awareness on initiatives to improve sustainability of fisheries, (k) fisheries sustainability initiatives undertaken by the non-state actors, (l) non-state actors or entities involved in fisheries sustainability initiatives, and (m) influence of fisher community groups in decision making.

(V) Fishing as a livelihood activity—this dimension represents the level of reliance of fisheries as a source of livelihood by the local community. It is based on a premise that present and future investments by fisher community toward fisheries demonstrate the willingness of the community to safeguard fishing as a livelihood activity (Kithiia 2011). We looked at two indicators on sustainability of fishing livelihood: (n) number of fishing hours in a day and number of years in fishing and (o) whether parents preferred fishing for occupation of their children.

(VI) Governance of climate change adaptation—governance of reef fisheries within climate change adaptation framework relates to the complex set of decisions to achieve social objectives for the use of natural resources (McIlgorm et al. 2010). We looked at two indicators of governance: (p) whether elected members or higher authority has been briefed on climate-mediated impacts or risks on fisheries, and (q) effectiveness of existing infrastructure.

To calculate the scores for each indicator by village, individual responses within each indicator were calculated using equation (I). These were then linearly stretched using equation (II) to obtain normalized scores with a value range of (0, 1). SAC dimension scores (i.e., partial SAC) were calculated as an average of the indicator scores. Finally, a final SAC metric with values ranging between (0, 1) was computed by synthesizing the partial SAC's from the six dimensions using the fuzzy sum operator (Zadeh 1965).

$$S = \frac{\sum_{i=1}^{N} V_i}{N} \times \frac{1}{t} \qquad (1)$$

where V_{i} is response for the variable considered N is the total number of respondents for each village t is the number of categories of the responses

$$\frac{S - S_{\min}}{S_{\max} - S_{\min}} \qquad (2)$$

where $S_{\min}$ = the minimum value for $SS_{\max}$ = the maximum values for S.

Finally, overall vulnerability metric was calculated by, firstly, synthesizing the village-scale ecological exposure with coral reefs ecological exposure indices. This was achieved through normalizing the RFEE values to between (0, 1) using equation (ii, where RFEE is substituted for S) and then subtracting the sum of the normalized RFEE and ecological index from their product (i.e., fuzzy sum operator, Zadeh 1965); second, by subtracting SAC from the synthesized exposure.

Results

National-scale climate exposure

Temporal trends of extreme temperature indices in PNG depict post-2010 as extremely warm period relative to historical baseline, even by the most conservative climate change scenario (i.e., RCP 2.6) (Fig. 1). Under this scenario, PNG is predicted to experience warm spells with maximum annual temperature reaching 31 °C compared to the historical baseline of 28 °C by 2050 (Fig. 1). The increasing trend of absolute temperature corresponds to an increase in warm spell duration (WSDI) and in the rate of exceedance of the historical extreme thresholds (TX90p) (Fig. 1).

Predictions indicate a more sporadic rainfall, with the number of dry spells (i.e., rainfall <1 mm) projected to decline in the coming decades (Fig. 1). This decrease in the frequency of the consecutive dry days coincides with increases in heavy and extreme rainfall days, overall signifying intensified rainfall associated with flooding. In addition, the frequency of extremely wet days, as indicated by the number of rainfall events exceeding 99th percentile of the historical baseline period, is predicted to increase considerably and faster than total wet day rainfall (Fig. 1).

Village-scale climate exposure

Similar to the nationwide assessments, village-scale assessments of climate exposure indicate increased frequency of temperature-associated extreme events into the future relative to present across all climate scenarios (Fig. 2). Moreover, results reveal differences among the villages, owing to the varying baseline SST, with offshore reefs off Ponam and Andra predicted to experience more frequent extreme events (i.e., ~7–11 annually) relative to near-shore sites (~5–7 events annually) (Fig. 2). Differences are more pronounced in the earlier years and in most optimistic scenarios. Projected behavior pattern of climate exposure, however, is similar for all villages, and depicts accelerated increase by 2050.

Coral reef exposure to climate change to date

Predictions of coral exposure show that relative to coral reef locations globally, reefs in Manus are on the extreme end of exposure index, with values ranging between 0.8

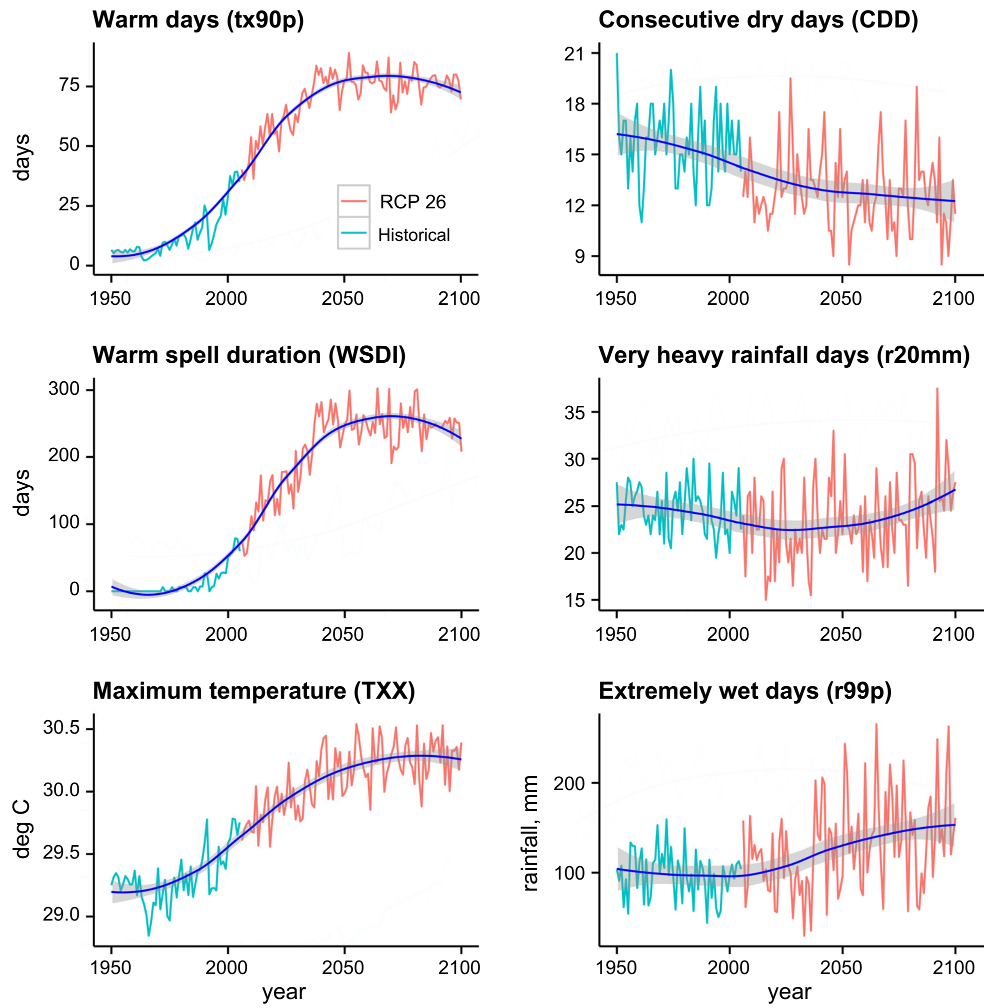

Fig. 1 Forecasts of temperature (**a**, **c**, **e**) and precipitation (**b**, **d**, **f**) extreme events for PNG based on indices derived from historical and RCP 26 climate model experiments

and 1 (Table 1). Exposure indices among reefs adjacent the five studied villages in Manus varied in magnitude, with the near-shore coral's off the mainland being relatively more exposed than those offshore off Andra and Ponam islands (Table 1). When the components of the multivariate stress model (i.e., climate and sediment) were evaluated separately, model predictions depict reefs off the mainland (Tulu, Pelipowai, Lahapau) as highly exposed to sedimentation relative to the offshore reefs off Andra and Ponam. When considering only climate dimension of exposure, Ponam Island and the mainland sites are highly exposed relative to the least exposed Andra. Overall, the ecological sensitivity of corals near the mainland sites is higher relative to the offshore reefs of Ponam and Andra (Table 1).

Social adaptive capacity

On a relative scale of (0, 1), SAC scores revealed differences among the five villages (Figs. 3, 4). Overall, Andra is associated with the highest SAC (0.84), while Tulu ranks lowest (0.53). Ponam was ranked second highest on the SAC scale (0.67), followed closely in third and fourth ranks by Lahapau (0.64) and Pelipowai (0.56), respectively. Andra scored highest in the following four of the six SAC dimensions: situation awareness, climate change risk perceptions, role of shadow state actors, and governance. Tulu on the other hand ranked lowest on overall SAC, scoring particularly low on SAC indicators of fishing as a livelihood activity, current adaptation options, and climate change risk perceptions. In Tulu, scores were relatively high for the situation awareness dimension, and for some indicators including: alternative livelihoods (current adaptation options dimension); involvement of non-state actors in efforts toward fisheries sustainability (role of shadow state actors dimension); and the effectiveness of infrastructure (governance dimension).

Integrating exposures and social adaptive capacity

An intersection of ecological sensitivity, climate exposure, SAC index illustrates the relative positions of

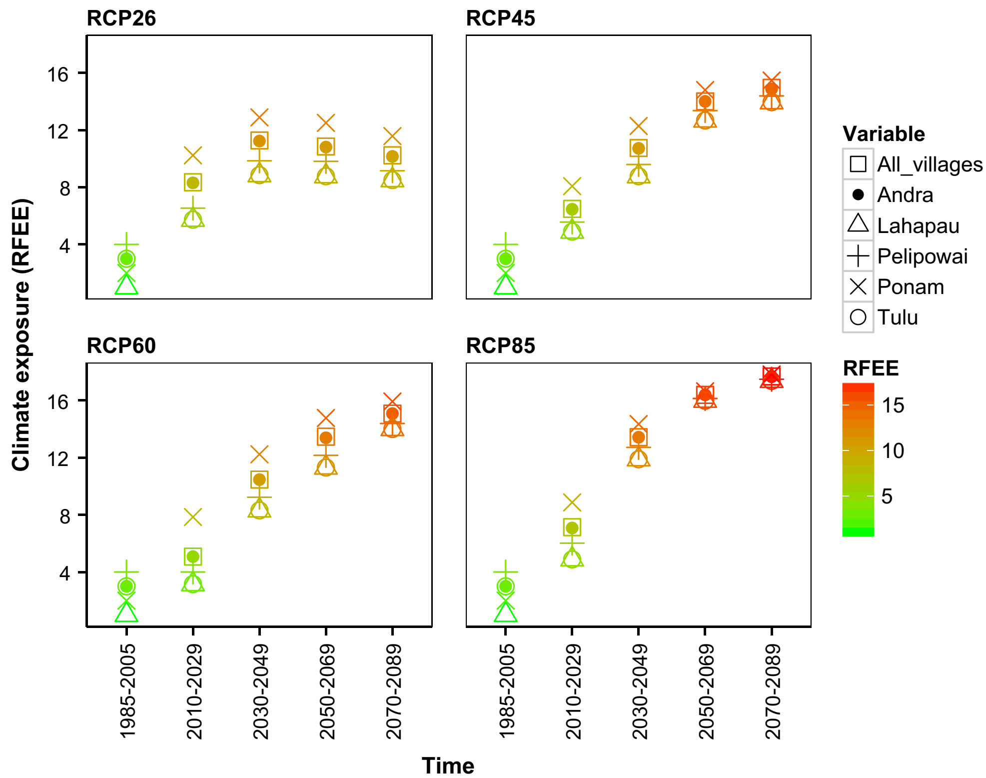

Fig. 2 Frequency of sea surface temperature extreme events (RFEE) for each village and climate change scenario, relative to historical baseline period (1985–2005). RFEE are presented for 20-year intervals of climate projections from 2010 to 2089. RFEE values are a median summary of five climate models. The associated confidence intervals (not shown on this Figure for clarity of the points) range from 1.2 to 2.3

Table 1 Coral exposure and sedimentation indices (0 = low, 1 = high) for each village as derived from the coral reef exposure model (Maina et al. 2011)

Village	Reef position		Sedimentation index	Coral exposure index
	Latitude	Longitude		
Ponam	−1.9110	146.887	0.23	0.91
Andra	−1.9380	147.002	0.19	0.90
Pelipowai	−2.2030	146.890	0.47	0.94
Lahapau	−2.0120	146.852	0.61	0.94
Tulu	−1.9520	146.830	0.66	0.94

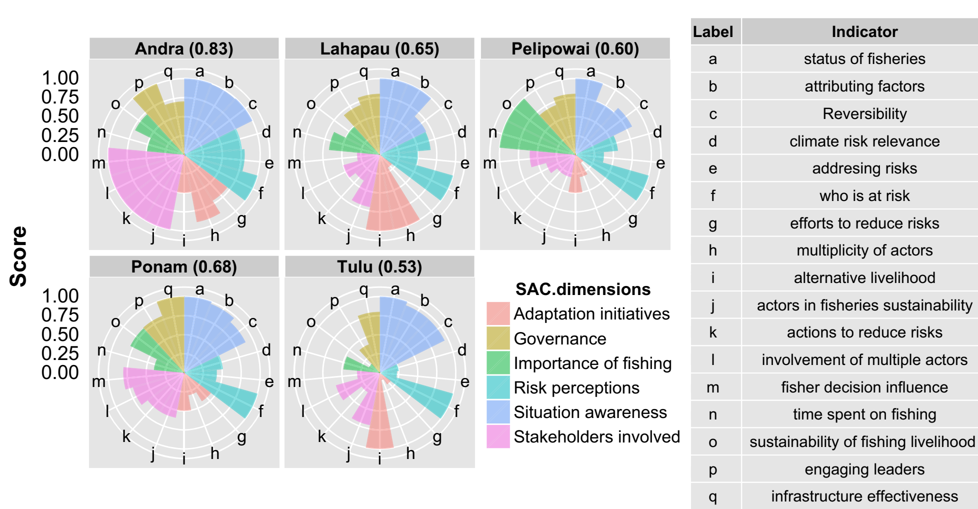

Fig. 3 Relative scores of indicators of SAC dimensions, grouped by village (*panels*). Indicators associated with each SAC dimension are represented by *bars* labeled with letters a–q and are listed on lookup table. In each of the plots, the more *color-filled* the *polar* plot (or the SAC space) is, the higher the SAC for the corresponding village. Overall, SAC indices for the villages are enclosed in parenthesis

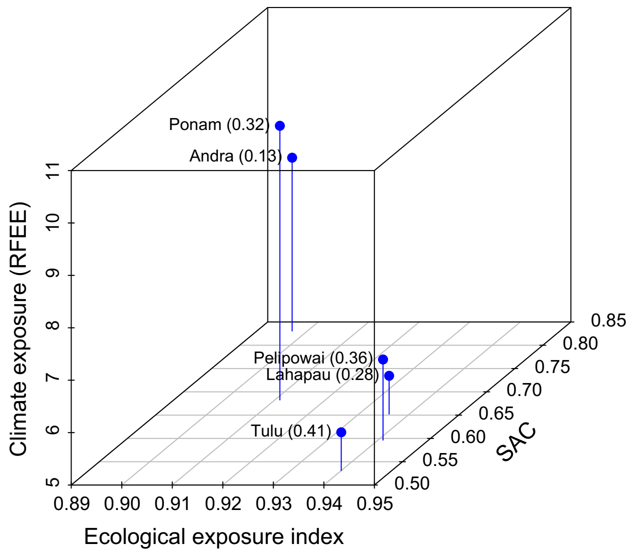

Fig. 4 Relative position of villages on the multidimensional vulnerability space defined by coral exposure index, relative frequency of extreme events (RFEE), and social adaptive capacity index (SAC). Overall, vulnerability indices for the villages are enclosed in parenthesis

villages in a vulnerability space (Fig. 4). The relative position of villages in the vulnerability space shows clustering by mainland–island basis. Mainland villages were clustered at high ecological exposure—low SAC—low climate exposure position on the multidimensional vulnerability space, while the island sites are positioned at relatively low ecological sensitivity—high SAC—high climate exposure position (Fig. 4). Climate exposure is highest in Andra and lowest in Tulu. When considering both ecological exposure and SAC dimensions of vulnerability, Andra is least vulnerable site among the island sites, while Tulu is the most vulnerable site among the mainland sites.

Discussion

In this study, we have demonstrated a framework that integrates information on: (1) the expected future climate (including climate-related extreme events) at the national and local (village) scale; (2) an ecological assessment of the impacts of these climate forecasts on coral reefs; and (3) the social adaptive capacity of the artisanal fishers (i.e., the ability to effectively prepare for, respond to, and recover from the impacts of these climate-mediated changes) can be used to assess the vulnerability of five coastal communities on Manus Island. This framework is an important advance in the field of climate adaptation because in addition to the ecological exposure dimension, the overall exposure metric now incorporates a dimension of exposure to future climate extreme events.

Overall, results indicate that despite relatively proximate geographies, there are differences among villages in social adaptive capacity and in environmental exposure. Here, we discuss each element of the integrated assessment in more detail.

Exposure to physical climate

Exposure to disturbances related to physical climate, as inferred in national-scale future projections of indices representing frequency, magnitude and duration of extreme temperature and rainfall events, are set to intensify with trends suggesting adverse weather impacts for PNG by 2050. Precipitation-related projections depict the region as generally wet with fewer consecutive dry days (CDD) with an increased flood risk (Fig. 1). According to our surveys, heavy rainfall, coastal flooding, sea-level rise, king tides, and extreme weather events are being experienced more frequently and intensely, especially on the islands of Ponam and Andra. These changes in climate are expected to impact economic activities related to fisheries, tourism, and agricultural sectors among others, in a region where adaptation planning is still in its infancy and the capacity of the local communities to cope with the ongoing changes is largely under-developed.

Village-scale analyses of climate exposure discerned village-scale differences in exposure, especially in the first two scenarios in earlier years (Fig. 3). However, in considering uncertainties in climate projections among the different models, and in the mismatch of the spatial datasets, adaptation planning for the village communities studied will be similar due to their geographical proximity. Notwithstanding these uncertainties, our study would seem to indicate a need for planning given the general shift toward increasing frequency of extreme events both at national and at village scales.

Coral reef exposure

Ecological sensitivity as inferred from the coral multivariate exposure model (Maina et al. 2011) showed that near-shore coral reefs off the mainland are relatively more exposed than the offshore reefs off Andra and Ponam islands. This finding is consistent with other studies that have reported more pressure on near-shore reefs relative to offshore reefs that are often shielded from chronic pollution, sedimentation, and overfishing that are more prominent inshore (e.g., Bak et al. 2005) (Table 1). Additionally, information elicited from the social surveys suggests that like in most reefs globally, corals in Manus are exposed to considerable anthropogenic pressures, including over-exploitation of fisheries and use of destructive fishing methods, coral harvesting, and nutrient and sediment as a result of deforestation, agriculture, as well as due to population increase (Online resource 4). This underpins the current global campaign to control sediment and nutrient pollution and to implement fisheries management strategies as the key measures for coral reef conservation and adaptation planning (Maina et al. 2013).

Social adaptive capacity

Our results provide critical insights into fisher community's SAC that might assist to sustain the fisheries resource. There is significant heterogeneity in SAC and the component indicators among fisher communities studied. Overall, fisher communities in Andra exhibited highest levels of SAC while Tulu displayed lowest levels. In fact, of the 16 indicators of the five dimensions of social adaptive capacity, those that represent situation awareness and risk perception dimensions varied the least among fisher communities. Analysis of these two dimensions found increased situation awareness in all villages. However, despite the seemingly high awareness, results suggest a general lack of predisposition to taking mitigative actions and inadequate preparedness. In consideration of the imminent climate extremes and the ecological changes, concerted efforts by the state and non-state actors to shift fisher communities from low or moderate levels of adaptive capacity are urgently needed.

Non-state actors can play a significant role in enhancing the social adaptive capacity, especially in developing countries, by among other things, helping to create the enabling structures around households and communities that influence local adaptation choices (Allen 2006). On evaluating the relative roles of non-state actors as one of the SAC indicators, overall, it appears NGOs, community clans and government agencies are the main actors in adaptation at grass root level where they facilitate different kinds of sustainability and adaptation activities. Notably, Andra village was found to host multiple actors in sustainability activities, with a heightened influence of fisher community and informal groups on policy and in decision making (Fig. 3). Tulu, Pelipowai, and Lahapau are some of the villages where more work may be required to encourage participatory governance of adaptation at grassroots level to promote local adaptation, which can potentially make a significant difference to household and community outcomes.

Apparently, there is a clear understanding by fishermen of human agency over the declined fisheries, as evidenced by the calls to perpetuate the traditional forms of closed/managed areas locally referred to as *Tambu*. Further, the fisher community across the villages perceives that leaving an area unfished for a period of time, and using nondestructive gear will enhance recruitment and lead to increased yield (Fig. 3, Online resource 4). Such awareness has been suggested as rarely informed by the ecological rationale that underpins establishment of permanent no-take zones to hedge against the recruitment failure and to promote spillover (Cinner and McClanahan 2006; Foale 2006). On the contrary, this understanding has been described as based on the common knowledge that leaving an area for a period of time leads to increased catch, rather than an understanding of the biological and ecological processes involved in the fish stock population dynamics such as growth rates and fish dispersal among other things (Foale 2006). Moreover, responses encountered in our survey and from previous studies (e.g., Cinner and McClanahan 2006) point to the fact that most reef-based subsistence fishers believe that the abundance of fish is ultimately divinely controlled. Therefore, as has previously been suggested (e.g., Foale 2006), basic education on the ecological underpinnings of adaptation actions targeted toward increasing fish stocks should be incorporated in the overall adaptation strategy, in order to enhance the adaptive capacity.

Results from evaluation of the importance of fishing as a livelihood activity as one of the SAC dimensions suggest that while some communities are keen on the maintaining fishing beyond the current generation, the majority of fishermen in Tulu view fishing livelihood as a less sustainable livelihood. This perception may stem from the apparent availability of more alternative livelihoods in Tulu, relative to other villages (Fig. 3). Surveys revealed that current efforts to promote alternative livelihoods include providing seeds for subsistence farming and for cash crops and promoting aquaculture (Online resource 4). At the same time, there is a need to safeguard the fishing livelihood through investments in key policy recommendations that broadly include: better management of fish stocks, establish marine protected areas, and supporting local livelihoods by employing local fishermen in safeguarding the habitat.

Combining the different dimensions of vulnerability

The location of the villages on the multidimensional vulnerability space bounded by coral exposure index, climate exposure, and SAC axes depicts Andra and Ponam as high SAC—high climate exposure—low ecological exposure sites, while the mainland sites of Tulu, Pelipowai, and Lahapau are depicted as relatively low SAC—low climate exposure—high ecological exposure sites (Fig. 4, Table 1). When considering only ecological exposure and SAC dimensions of vulnerability, it would appear that island communities are the least vulnerable, compared to those on mainland. However, incorporating a new dimension of exposure in the vulnerability space (i.e., downscaled extreme events) depicts island communities as the most exposed to climate extreme events, and on the whole are as vulnerable as the communities on the mainland. This demonstrates that integrating climate extreme events in these analyses provides a more comprehensive assessment of the vulnerability of a socioecological system and is a step closer to representing the totality of a human–bio-physical coupled system.

These results indicate, overall, that only some fisher communities will have the capacity to respond appropriately to policies and practices that enhance climate adaptation. Yet, by 2050, fisher communities in Manus and the region as a whole will be experiencing extreme rainfall with possible flooding and high-temperature events (Figs. 1, 2). Our results suggest that the heterogeneity in social adaptive capacity that currently exists in fisher communities studied will have profound influence on the sustainability of the social–ecological fisheries system. These differences also provide the adaptation management with an opportunity to assess the effectiveness of the current adaptation strategies in different villages and to identify successful strategies that need to be replicated or adapted to other villages. Overall, any single initiative to address fisheries sustainability practices in Manus villages is unlikely to address the needs of all communities. Rather, policies could be spatially adaptive and tailored to type-specific needs based on the adaptive capacity of fisher communities, and on relative exposure of the socioecological system to climate extremes events. Moreover, the scale of adaptation planning needs to be smaller, as there is a lot of variability even within the villages that are closer.

Caveats and future research

This paper has outlined an important first step in integrating key aspects of exposure and social adaptive capacity and shows that data can be collected and collated in a way that is meaningful for adaptation assessment and planning. However, we recognize a number of ways future studies could potentially improve the assessments. We investigated social impact pathways through fisheries, as this is the primary mechanism for getting food. However, climate change may impact a range of livelihood activities, especially agriculture and future studies may wish to consider key impacts to agriculture in the exposure metrics and include agriculture-specific indicators of adaptive capacity.

Conclusions

Climate forecasts are seldom integrated in local planning due to a range of reasons, including lack of better spatially resolved climate data and difficulties in translating raw climate data into simple indices of extreme events. However, amid growing social and environmental uncertainties to climate change, it is urgent to consider future climate conditions, as anticipatory adaptation plans can allow for planning that makes sense in both the short and long term. Using a novel framework, we have demonstrated that it is possible to integrate social, ecological, and climate data at a local scale so that it can reveal differences between villages. By focusing on enhancing the five dimensions of adaptive capacity and taking into consideration ecological and climatological dimensions of exposure, we think that it is possible to bring closer the necessity of climate smart adaptation planning to improve fisheries sustainability at smaller spatial scales.

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