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Developing signals to trigger adaptation to sea-level rise

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Supplementary material for this article is available online

Abstract

Dynamic adaptive policy pathways (DAPP) is emerging as a ‘fit-for-purpose’ method for climate-change adaptation planning to address widening future uncertainty and long planning timeframes. A key component of DAPP is to monitor indicators of change such as flooding and storm events, which can trigger timely adaptive actions (change pathway/behavior) ahead of thresholds. Signals and triggers are needed to support DAPP—the signal provides early warning of the emergence of the trigger (decision-point), and the trigger initiates the process to change pathway before a harmful adaptation-threshold is reached. We demonstrate a new approach to designing signals and triggers using the case of increased flooding as sea level continues to rise. The flooding frequency is framed in terms of probable timing of several events reaching a specific height threshold within a set monitoring period. This framing is well suited to adaptive planning for different hazards, because it allows the period over which threshold exceedances are monitored to be specified, and thus allows action before adaptation-thresholds are reached, while accounting for the potential range of timing and providing a probability of premature warning, or of triggering adaptation too late. For our New Zealand sea level case study, we expect early signals to be observed in 10 year monitoring periods beginning 2021. Some urgency is therefore required to begin the assessment, planning and community engagement required to develop adaptive plans and associated signals and triggers for monitoring. Worldwide, greater urgency is required at tide-dominated sites than those adapted to large storm-surges. Triggers can be designed with confidence that a change in behavior pathway (e.g. relocating communities) will be triggered before an adaptation-threshold occurs. However, it is difficult to avoid the potential for premature adaptation. Therefore, political, social, economic, or cultural signals are also needed to complement the signals and triggers based on coastal-hazard considerations alone.

1. Introduction

Rising sea level is already causing more frequent flooding along many coasts globally [1–3], and in future will greatly increase the frequency and consequences of flooding [1, 4], and cause saltwater intrusion into groundwater and rivers, geomorphological adjustment of the coastline, rising groundwater levels and vegetation change [5]. Expected sea-level rise (SLR) of 0.5–2.0 m could displace 72–187 million people globally [6]. Exposed communities must adapt to these consequences, but planning is complicated by deep uncertainty in the height and timing of storm-tides and SLR, which drive flooding [3, 7, 8]. We address a key supporting mechanism for implementing adaptation actions, by showing how early signals (warnings) and triggers (decision-points) can be designed to initiate adaptive action before coastal flooding reaches an adaptation-threshold beyond which undue harm occurs and costs of adaptation increase.

Flooding can occur during very high tides [9], or during storm-surges when low atmospheric pressure and strong winds drive the sea over land [10], and these processes can combine to produce very high storm-tides. The rate of SLR is projected to accelerate,

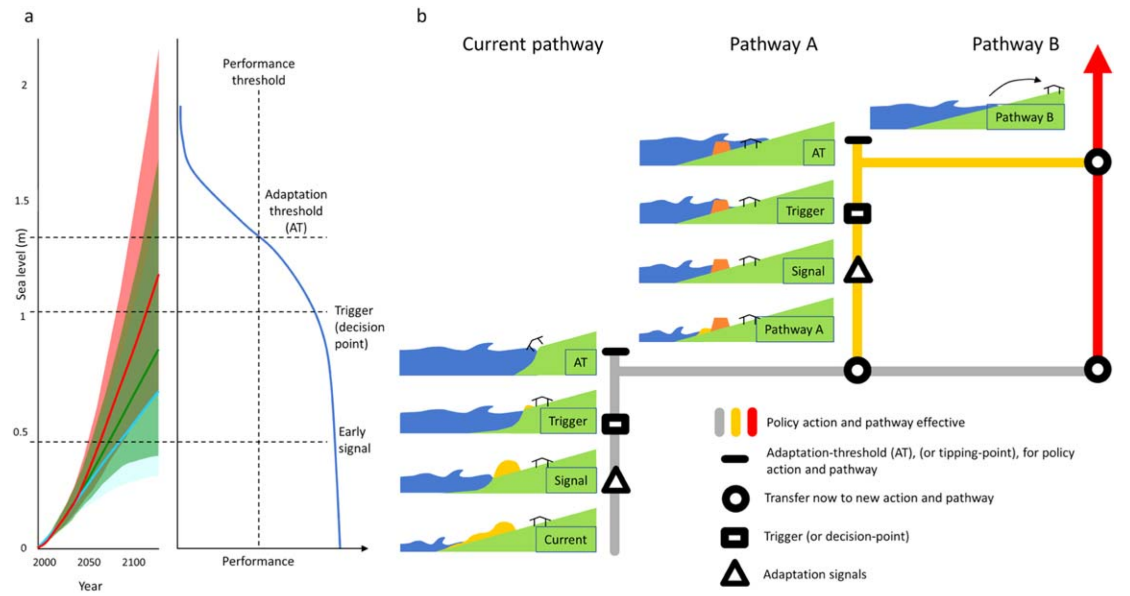

Figure 1. Key concepts for adaptive actions to SLR. (a) Probabilistic SLR projections for RCP2.6, RCP4.5 and RCP8.5 scenarios from Kopp *et al* [33] showing median projection (line) and 95% confidence intervals (shaded), along with a schematic illustrating adaptation-threshold, trigger (decision-point) and early signal in relation to SLR and pathway performance. (b), illustrated dynamic adaptive policy pathways example where pathway A shows a sea wall whereas pathway B shows managed retreat (after [16]).

driven mainly by the cryosphere and ocean response to warming from greenhouse gas emissions [6, 11, 12]. SLR will raise the height of storm-tides, causing an increase in their frequency reaching levels now considered to be 'extreme' [4, 10], and will cause increasingly frequent 'nuisance' flooding from smaller and more frequent storm-tide events [1].

Adaptation can include avoidance, accommodation, protection and more transformative actions such as managed retreat [5]. Methods for planning under conditions of uncertainty are being used increasingly, separately or together, for problems like SLR [13]. Adaptation pathways planning has emerged as a way to frame future adaptation decisions [14–21]. It is based on the principle that adaptation cannot be undertaken through a single action in the context of deep uncertainty, but is rather a process to be managed over time as conditions change [14]. Dynamic adaptive policy pathways (DAPP) [16, 19], which merges the concepts of adaptation pathways and adaptive policymaking, is emerging as a 'fit-for-purpose' method for climate-change adaptation planning to address widening future uncertainty and long planning timeframes [16, 18, 22].

The DAPP process enables a series of interlinked pathways to be developed, where 'signals' of change are needed to alert the decision maker of a pending 'trigger' (time when a decision should be made) to switch pathways (figure 1) [16, 17, 23, 24]. The trigger must provide sufficient lead time to adapt before the 'adaptation-threshold' is reached [18]. Initiating change to another pathway may be delayed if slower than anticipated SLR occurs, or an earlier change may be implemented if SLR is more rapid than expected—emphasizing the crucial role of monitoring and reviewing triggers [16, 18, 25]. Modeling can also be used to anticipate the arrival of signals, triggers and adaptation-thresholds, but due to uncertainty in timing, the actual decision must be linked to monitoring of environmental and social tolerance indicators.

An 'adaptation-threshold' (or adaptation tipping point [23]) occurs when the present pathway is no longer effective in meeting objectives and a new action or pathway is necessary. Adaptation-thresholds are associated with performance of the system of concern, for example storm-tide flooding becoming too frequent for a viable community to function or, when beach nourishment or a sea wall is no longer effective due to technical, economic, or social limitations. Adaptation-thresholds also relate to the coping capacity of people as service levels change and losses and harm occurs (figure 1). Adaptation-thresholds are often framed in terms of extreme events [18] that cause social disruption [14], but can be identified through community engagement [14, 18, 22] and/or detailed modelling and risk assessments [3, 15, 18] ahead of such events.

Monitoring for early signals of an approaching trigger is an essential component of DAPP [25]. Comparing observed events (like storm-tide frequency) with their pre-specified trigger-values, enables decisions to be made on whether adaptation actions need to be taken; monitoring for signals and triggers enables timely adaptive actions to be taken [18]. Identifying, evaluating and using indicators to develop adaptation-thresholds, signals and triggers for climate adaptation has received little attention in the literature so far [18, 21]. Signals function as 'early warning' that objectives may be compromised (through under-performance of the system) and should initiate planning and stakeholder engagement on the next pathway or action to implement at the trigger. However, in practice, decision makers tend to trigger adaptation actions in response to extreme events as they occur [18], because they have immediate and discernible (social and economic) impacts [14] and generate pressure from affected communities to act.

Although climate-change indicators can be monitored and observed using mean values, for which long-term trends can be identified, e.g. mean sea level (MSL), trends are less evident in the extreme (storm-tide) events. Extreme events are strongly influenced by the effects of climate variability on storms [26], and this variability makes it difficult to detect climate-change trends in extreme values or the emergence of underlying SLR trends [27], and difficult to predict the timing of extremes [18, 26]. Therefore, decisions to adapt are often made in response to extreme—rare—events, but the randomness of extreme events in time makes extremes difficult to apply as early warning signals [18]. Furthermore sequences of early extreme events could provide a premature warning signal, resulting in too early adaptation, whereas delay in the occurrence of extremes could trigger adaptive actions too late, leaving insufficient time to adapt [18]. This led Haasnoot *et al* [18] to emphasize the importance of knowing the spread of timing of signals and relating this to the potential of premature warnings.

In this paper we present a new approach to developing physical signals and triggers for DAPP, illustrate its application using a New Zealand (NZ) coastal example, and compare it to several international sites. Rather than use MSL trends or incremental change to develop signals and triggers, we instead used increases in the frequency of smaller storm-tides, to signal the future increase in frequency of large storm-tides, which could be tied to an adaptation-threshold. The basis for the method is that the adaptation-thresholds, signals and triggers are based on incidences of storm-tide thresholds being reached. Although the adaptation-thresholds, which we aim to avoid, are likely related to extreme sea-levels, the trigger levels and signals need not be extreme—we can monitor less-extreme events to trigger adaptation before the thresholds are reached. We modeled the probable time window (time range) of the start of a sliding 10 year monitoring period within which a specified number of exceedances of a threshold sea-level elevation are expected. This is a major improvement in the framing of hazard information for adaptation planning because time is a critical element; the approach is congruent with monitoring periods and adaptive planning timeframes used by decision makers. Moreover, the approach provides a way to design signals and triggers relative to the adaptation-thresholds, accounting for uncertainty and the spread of timing of signals and the probability of premature warnings, thus addressing a key barrier to the implementation of adaptation actions.

2. Methods and data

2.1. Background and method advancement

Previous studies of the likelihood of flooding driven by storm-tides and SLR have generally focused on three themes, which have given little attention to the future timing of flooding events:

1. Estimation of the likely increase in the frequency (and its uncertainty) of extreme sea levels [4, 10] and of nuisance flooding [1]. These studies have shown that flooding frequency will increase dramatically with a modest SLR, and provide evidence of the need to adapt.
2. Identification of the sensitivity of increasing flood hazard [28, 29] and risk [8, 30] to various drivers of coastal flooding, including both storm-tide and SLR. These studies show that uncertainty in the storm-tide distribution can dominate the uncertainty in the calculation of extreme sea-level return periods and associated risk, particularly at relatively short timescales out to approximately 2050–2080 [7, 28], whereas widening SLR uncertainty begins to dominate thereafter.
3. Estimation of flood-barrier height adjustment from historic flood levels that would maintain the annual expected probability of flooding under uncertain SLR conditions [4, 31, 32].

To address timing, we have designed a new metric with uncertainty bounds: the probable time window of the start of a sliding $T = 10$ year monitoring period within which a specified number of exceedances N are expected, of an adaptation-threshold and its associated signals and triggers. We evaluated this metric using probabilistic SLR projections and their uncertainty to the year 2200 [33]. The method quantifies the sea-level height threshold, its frequency in terms of the expected number of events within the coming years, and the probable time range (due to uncertainty) over which the threshold is likely to be realized. The method is flexible in allowing choice of threshold and number of events over time, enabling thresholds to be co-designed to accommodate social, economic, and cultural, values and aspirations.

2.2. Choice of signal, trigger, and adaptation-threshold

To demonstrate the method, for our NZ case studies, we chose an adaptation-threshold as an increase in the frequency of storm-tide events associated with a 1% annual exceedance probability (AEP), from 1% AEP at present-day MSL to 50% AEP in future, a shift from one event about every 100 years to five about every

10 years on average. 1% AEP events are often used in hazard analyses because they are large and rare storm-tide events that can cause damage [3, 26]. In practice, adaptation-thresholds would be determined through a community engagement process to ensure relevancy and community support, to enable effective implementation of the adaptive plan [14, 15, 18, 19, 22].

The signal and trigger were chosen relative to the adaptation-threshold, based on the probability that they would occur before the adaptation-threshold was reached. The early signal was chosen as the start of a sliding 10 year monitoring period in which 5 × 18% AEP events (evaluated at present-day MSL) are expected to occur. The trigger to change the adaptation pathway was chosen as the start of a sliding 10 year monitoring period in which 5 × 5% AEP (less frequent) events are expected to occur. A $T = 10$ year monitoring period was chosen, because it often matches the lifespan of coastal land-use plans (e.g. NZ), and it is long enough to observe discernable changes as the sea level continues to rise. The signal and trigger were ascribed respectively to 'minor' and 'moderate' extreme events today, which will become more frequent with SLR. We have high (80% probable) to medium (50% probable) confidence [34] that they will occur before the chosen adaptation-threshold, respectively. The timing probabilities are based on the combined uncertainty of the storm-tide and SLR distributions, and their calculation is described in the supplementary material is available online at stacks.iop.org/ERL/13/104004/mmedia. For example, if the more frequent 18% AEP event occurs five times in 10 years, later followed by the 5% AEP occurring five times in 10 years, this would signal that the 1% AEP event may soon occur five times in 10 years. The early signal provides a warning of the emergence of the trigger, and the trigger initiates the process to change pathway before the adaptation-threshold is reached.

A complication with monitoring just the mean sea-level trend, is that annual MSL does not follow a smooth trend. It includes variability caused by the Interdecadal Pacific Oscillation and the El Niño Southern Oscillation, which are highly variable over a 10 year monitoring period, leading to variability in MSL, plus variability in tide and storm surge. Therefore, we prefer to monitor to account for the full variability of MSL + tide + storm-surge when developing signals and triggers.

2.3. Sea-level data

We used hourly sea-level records (figures S.1–S.3) to identify signals and triggers for adaptation to coastal flooding, as sea level continues to rise. Hourly sea-level records were quality-analyzed to remove any spikes, timing errors, or datum shifts. The sea level heights are specified relative to local vertical datum [35]. The data were linearly detrended and the means removed before further analysis, to remove the effects of historical SLR from the sea-level distribution. We used a linear trend rather than removing annual MSL because we wished to retain inter-annual sea-level variability in the storm-tide distribution.

2.4. Summary of detailed methods

The supplementary material contains a detailed description of the SLR scenarios used, the mixed sea-level distributions, and how exceedance statistics were calculated. Here we summarize the methods.

Previous studies have tended to focus separately on either 'extreme' [4, 10] sea levels or 'nuisance' [1] flooding. We have used a mixed-distribution model [36, 37], which allows us to estimate the changing frequency of smaller, more frequent storm-tides which are used to design signals and triggers, while simultaneously modelling the changing frequency of more extreme storm-tides as adaptation-thresholds to be avoided. The mixed distributions for six NZ coastal-gauge sites are shown in figure 2, and compared with Auckland (NZ) at six international sites in figure 3. The NZ sites (figure 2) exhibit a gently rising sea-level distribution toward low AEP; elevation differences between the distributions are driven mainly by differences in tidal range. The international sites (figure 3) include a variety of tidal range and tide/surge dominance [38, 39]; Cabo San Lucas and Zanzibar are strongly tidally-dominated, exhibited by very flat sea-level distribution at low AEP; Cuxhaven and Galveston are surge-dominated, exhibited by steeply rising sea-level distribution at low AEP; Auckland (representative of NZ) and Newlyn are surge-modified tidally-dominated, exhibited by gently rising sea-level distribution at low AEP. Cabo San Lucas and Galveston have relatively small tides, exhibited by small sea levels at high AEP, while Auckland, Zanzibar, Cuxhaven and Newlyn have relatively large tides as exhibited by larger sea levels at high AEP.

Like most other studies we have relied on the historical storm-tide distribution, and assumed that this will remain stationary in a changing climate, and that any non-stationary effects on total water level will be of second order to SLR e.g. [1, 4, 8, 10, 28, 31, 40]. Climate change will cause changes in the frequency and intensity of storms, which will affect storm-surge [41], but future projections are not well resolved yet [41]. SLR will also affect tidal amplitudes, but these affects are yet to be estimated in most places [42].

We used the mean global SLR projections of Kopp, *et al* [33], who provided separate projections in response to forcing from RCP 2.6, 4.5, and 8.5 conditions, which correspond, respectively, to likely global mean temperature increases in 2081–2100 of 1.9 °C–2.3 °C, 2.0 °C–3.6 °C, and 3.2 °C–5.4 °C above 1850–1900 levels [12]. An additional 2 mm yr^{-1} relative SLR was

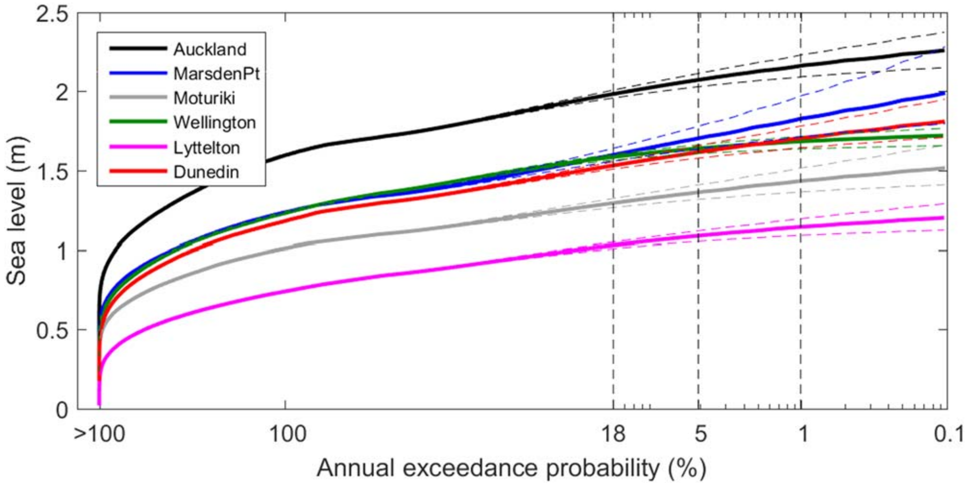

Figure 2. Mixed distributions of the measured sea level at the six NZ sites, after removal of long-term linear trend. All sites exhibit a gently rising sea-level distribution at low annual exceedance probability (AEP), and elevation differences between the distributions are driven mainly by differences in tidal range (with tides dominating the high-frequency sea levels). The solid lines mark the medians, and dashed lines mark the 95% confidence intervals. Sea level is plotted relative to a MSL of zero (no local vertical datum offset).

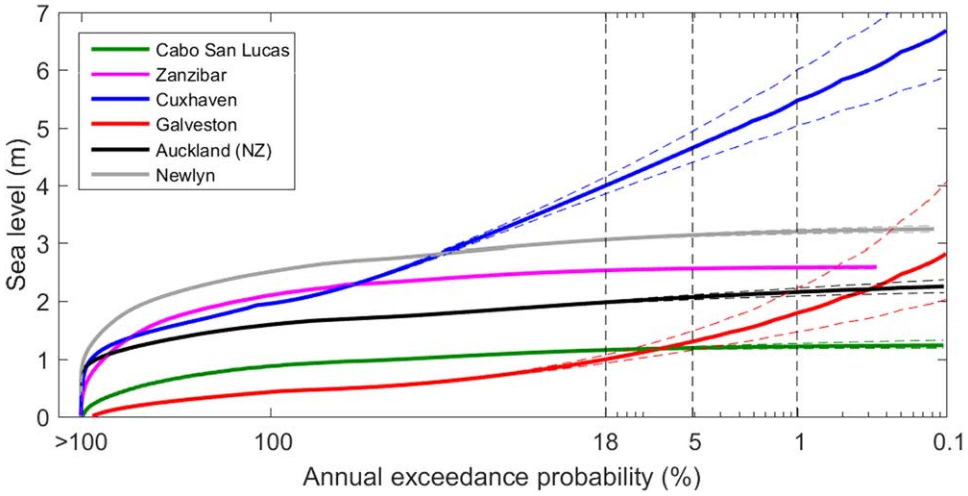

Figure 3. Mixed distributions of the measured sea level at international sites, after removal of long-term linear trend. The solid lines mark the medians, and dashed lines mark the 95% confidence intervals. Cabo San Lucas and Zanzibar are strongly tidally-dominated, exhibited by very flat sea-level distribution at low AEP. Cuxhaven and Galveston are surge-dominated, exhibited by steeply rising sea-level distribution at low AEP. Auckland (NZ) and Newlyn are mixed tide-surge-dominated, exhibited by gently rising sea-level distribution at low AEP. Cabo San Lucas and Galveston have relatively small tides, exhibited by small sea levels at high AEP, and vice versa at other sites.

added to the projections at Wellington NZ, to account for vertical land movement [43].

We convolved the SLR probability distribution with the exceedance probability from the mixed-distribution model of storm-tide (which is assumed to stay constant over time), to produce a unique total sea-level probability distribution through time, following Hunter [44].

Equations (S.1)–(S.3) were used to calculate the expected timing and its uncertainty of the start of the $T = 10$ year monitoring period when we would expect to see $N = 5$ events occur for each of the 1%, 5% and 18% AEP thresholds (respectively the adaptation-threshold, trigger and early signal), (figures S.6 and S.7).

3. Results

Figure 4 shows the expected timing of the start of the sliding 10 year monitoring period in which the chosen adaptation-threshold, early signal and trigger will be reached, evaluated for three SLR scenarios, for six sea-level site records in NZ (figure S.1). The median values show that the signals are generally expected to occur before the triggers, and the triggers before the adaptation-thresholds are reached, but there is overlap between the time windows. These are windows of time for which we have a specified confidence of reaching the adaptation-thresholds (AT), signals and triggers across SLR projections. Figure 4 shows medium (50%) and high (80%) confidence windows. It is generally

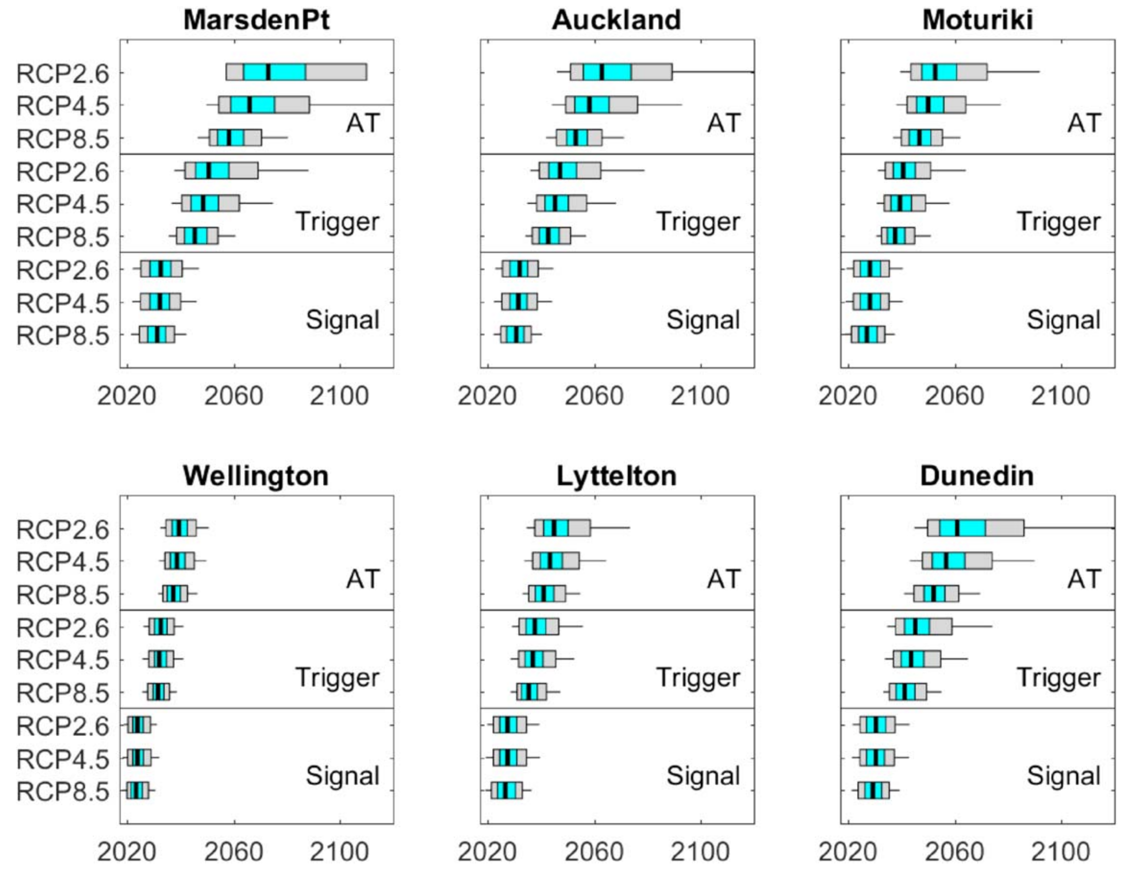

Figure 4. Time of the start of the $T = 10$ year monitoring period in which the adaptation-threshold (AT) and its early signal and trigger are expected to be reached, for the NZ case adopted. At each site, the adaptation-threshold is shown in the top frame, with the trigger and early signal in the middle and lower frames respectively. Central vertical bar marks median projection. Grey box marks 80% confidence intervals = 'highly confident', and light-blue box marks 50% confidence intervals = 'medium confidence'. Horizontal black line marks 95% confidence intervals. It was not possible to determine the 95% confidence interval range for RCP2.6 scenario at Marsden Point, because the upper 95% limit was not reached by the year 2200.

possible to have high confidence that the adaptation signal will occur before the adaptation-threshold, but only medium confidence that the trigger will occur before the adaptation-threshold. The median expected timing of the start of the 10 year monitoring period for the adaptation-threshold, early signal and trigger, across all sites and all SLR scenarios, are the years 2054, 2043 and 2030 respectively, although there is considerable variation depending on site within NZ and SLR scenario (figure 4).

Adaptation-thresholds, signals and triggers, are expected to be reached earlier for faster SLR scenarios and vice versa. The time windows are wider for slower SLR scenarios, and vice versa.

The timing of the adaptation-threshold is sensitive to the SLR scenarios. The timing of early signals and triggers is less sensitive because they are based on higher-frequency storm-tides which are predicted to occur earlier, and because the uncertainty bands of the SLR scenarios are close together over the next few decades [33].

We have medium confidence that the triggers will be observed at all 6 NZ locations and for any SLR scenario, in the 10 year monitoring periods starting between 2033–2063 and high confidence that the early signals will occur in the 10 year monitoring periods starting between 2021–2043, depending on location. The median projection between all 6 locations and for all SLR scenarios is for the early signals to occur in the 10 year monitoring period starting 2030, in NZ. Some urgency is therefore required to begin the assessment, planning and community engagement for developing adaptive plans before adaptation triggers are reached.

We designed our signals and triggers relative to the chosen adaptation-threshold, such that the triggers would likely occur, and the signal would very likely occur (in the calibrated uncertainty language of the IPCC [45]) before the adaptation-thresholds. The chosen adaptation-thresholds were based on more frequent occurrence in future of a 1% AEP storm-tide, so it assumes that there is presently a hazard exposure to a 1% AEP storm-tide, which is true for many coastal locations in NZ. But for areas at higher elevations, hazards will emerge later and with higher SLR, and the timing will be critically linked to the rate of future SLR within ever-widening uncertainty bounds (Kopp *et al* 2017). Higher-elevation adaptation-thresholds and their signals and triggers, will have slower onset, and wider time (confidence) windows than indicated in figure 4.

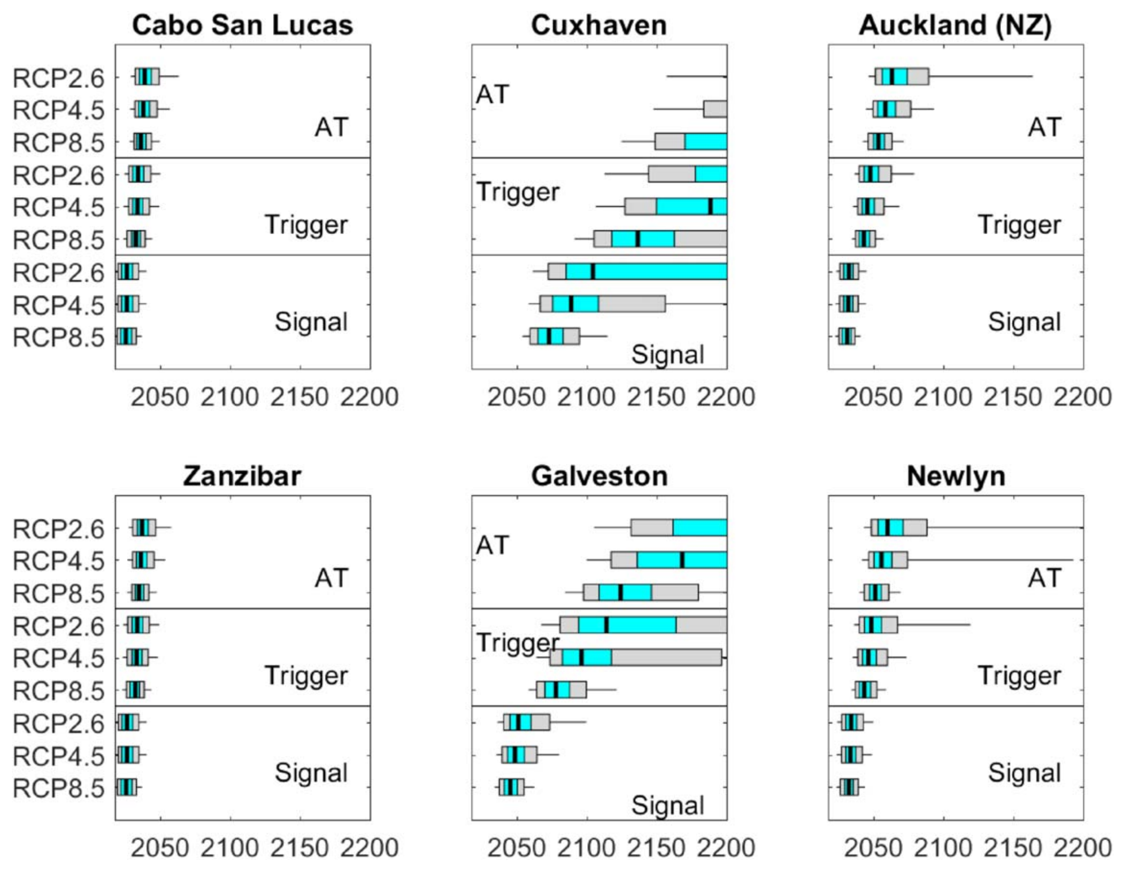

Figure 5. Time of the start of the $T = 10$ year monitoring period in which the NZ-derived adaptation-threshold (AT) and its early signal and trigger are expected to be reached, at international sites. At the tide-dominated sites Cabo San Lucas and Zanzibar, the timing of the three NZ-derived threshold indicators is compressed. At the surge-dominated sites Cuxhaven and Galveston, the timing of the three NZ-derived threshold indicators is delayed.

We then tested the NZ-derived adaptation-thresholds, signals and triggers at the international sites (figure S.2), and found that they are not universally applicable (figure 5), although they behave similarly at Newlyn, which has a similar mixed tide/surge regime to NZ sites. At the tide-dominated sites Cabo San Lucas and Zanzibar, the timing of the three NZ-derived threshold indicators is compressed; the adaptation-thresholds derived for NZ conditions will occur earlier at tide-dominated sites, leaving insufficient time to develop clear signals and triggers—the signals are already occurring so there may only be time to develop triggers for when to adapt. At the surge-dominated sites Cuxhaven and Galveston, the timing of the three NZ-derived threshold indicators is delayed, and there is greater overlap between the uncertainty windows between the signal, trigger and adaptation-threshold. Therefore, adaptation-thresholds, signals and triggers need tailoring to local conditions, discussed below.

4. Discussion

4.1. Our method makes the following advances:

- Accounts for the probable time range (time window) of the start of a sliding T-year monitoring period when a specified number N-exceedances of a threshold sea-level elevation are expected. This enables the framing of hazard information for planning to adapt with time as well as between sites [14].
- Accounts for the full sea-level distribution rather than focusing exclusively on either large and extreme, or smaller and more common nuisance flooding events. This enables smaller more frequent events to be used to signal increasing frequency of larger, more extreme events.
- Allows the same variable of interest, total storm-tide water level in our case, to be used to design signals, triggers and adaptation-thresholds for pathway change before those thresholds are reached, thus simplifying the monitoring for adaptive planning.

Our approach also addresses the critical challenge associated with the difficulty of designing signals and triggers to account for uncertainty in both SLR projections and the timing and sequencing of storm-tides. This is necessary to show the probable range of timing of signals and whether there may be premature warnings.

From our case study, the relative insensitivity of the chosen signals and triggers to SLR scenario in the

Table 1. Description of tide/surge regime for the study sites, and the annual exceedance probability (AEP) and number of events (*N*) in a $T = 10$ year monitoring period, used to demonstrate the development of adaptation-thresholds, signals and triggers for NZ (figure 4) and international (figure 6) sites.

		Adaptation-threshold		Trigger		Signal	
Site	Description	AEP (%)	*N*	AEP (%)	*N*	AEP (%)	*N*
NZ sites	Surge-modified	1	5	5	5	18	5
Newlyn (UK)	Surge-modified	1	5	5	5	18	5
Cabo San Lucas (Mexico)	Tide-dominated	0.2	50	1	10	2	5
Zanzibar (Tanzania)	Tide-dominated	1	50	2	10	5	5
Cuxhaven (Germany)	Surge-dominated	5	3	10	3	18	3
Galveston (Texas, USA)	Surge-dominated	5	3	10	3	18	3

near-term is helpful in one sense, because it reduces the influence of uncertainty of SLR scenario choice on the decision-making process [3]. Then again, the results indicate that some urgency is required for adaptive planning or it will be too late. If the early signal indicator used here is taken as the signal to prepare for the implementation of the next pathway before the trigger is reached, then a full strategic assessment, planning and community engagement process needs to begin now to map out future pathways—as such a signal could occur in the 10 year monitoring period starting 2021 onwards (based on the 80% confidence time windows in the NZ illustration). NZ is in a transition zone between tide/storm-surge/wave dominance [39], but globally, mean annual maximum water levels are dominated by tidal variability with relatively small storm-surges [38, 39], which makes them sensitive to SLR [39, 46]. Therefore, many locations around the world will be even more sensitive to SLR than NZ, in terms of the timing of signals, triggers and adaptation-thresholds, except for areas that experience tropical cyclone activity and large storm-surges.

The steepness of the extreme tail of the sea-level distribution is a key control on the timing of high sea-level thresholds (at present-day MSL) being reached after a period of SLR (figures 5, S.9, S.10) [4, 31]. For strongly tide-dominated sites with very flat extreme sea-level distributions (figure 3), to derive signals and triggers whose uncertainty windows are clearly separated in time, requires setting a higher adaptation-threshold than used in NZ (e.g. lower AEP or more events, table 1, figure 6). Conversely, for storm surge-dominated environments with steep extreme sea-level distributions (figure 3), adaptation-thresholds for NZ conditions are unlikely to occur by 2200 (the limits of probabilistic SLR projections). The severe consequences of these large surge events (e.g. 2012 Hurricane Sandy in USA and the 1953 North Sea flood) suggests lower adaptation-thresholds than for NZ (e.g. higher AEP or fewer events, table 1), with associated timely signals and triggers (figure 6). A conclusion is that tidally-dominated sites will reach damaging thresholds earlier and require greater urgency of attention, which is consistent with previous findings that tidally-dominated sites will experience a greater increase in flooding frequency with SLR, and require higher design height allowances to preserve present-day flooding frequency after SLR [4, 31, 46, 47].

The continuous mixed-distributions (figure 3) model the changing likelihood of low to high sea-level threshold exceedances at all sites, providing a means to design adaptation-thresholds, signals and triggers despite different sea-level forcing regimes like tide dominated at Zanzibar, tropical cyclone surge dominated at Galveston, or extra-tropical (winter) storm dominated at Cuxhaven. Extreme-value distributions used in other studies [4, 31, 44, 47] are less accurate for modeling the changing likelihood of sea-level threshold exceedances with SLR, particularly at tide-dominated sites where only a small SLR is required to move beyond the valid range of the fitted extreme-value model.

Figures 4 and 6 show that it is difficult to choose a signal or trigger that we are confident will occur before the adaptation-threshold, but will not occur several decades before the adaptation-threshold, i.e. we want it to be timely, but could easily be over-conservative. This difficulty arises because there are overlaps between the signal/trigger/threshold windows, once the uncertainty of occurrence and probable timing is accounted for (figure 4). These overlaps suggest that it may be difficult to develop signals and triggers based solely on physical hazard considerations.

Over a multi-decadal planning period, societal and economic values, aspirations and conditions will change [25]. This suggests that complementary socially-defined signals and triggers will also be needed to reflect the coping capacity of communities and services and therefore what policy choices have relevance, credibility and legitimacy for managing coastal change [48], and thus can be implemented through the prevailing institutional arrangements. Methodologically, such signals and triggers could complement the physical ones developed here, by triangulating the results as part of a validation process [49]. A combination of signals and triggers could be used for adaptation actions and pathways choices that encompass: hazard-based (e.g. damage to or loss of habitat or built environment); risk-based (e.g. frequency of *X* amount of damage or loss of service over *Y* timeframe); socially-based (e.g. loss of amenity, unacceptability or not

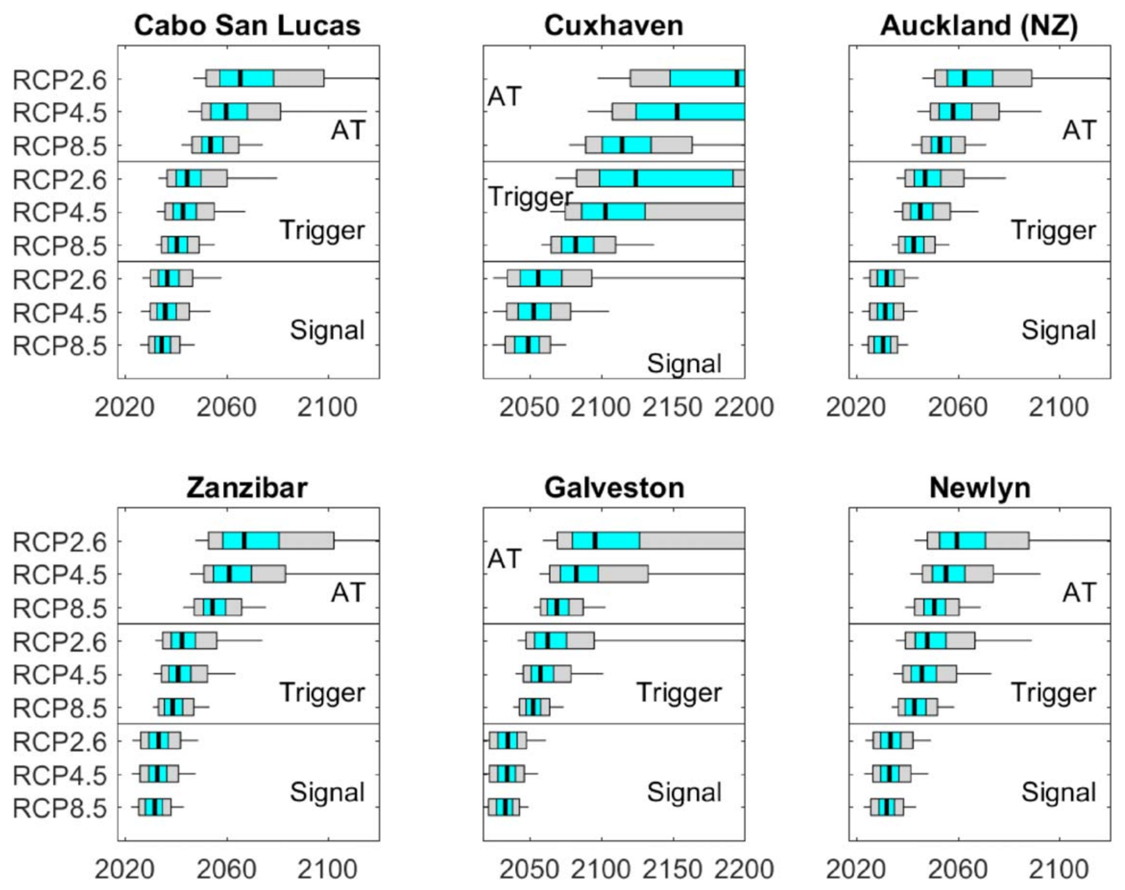

Figure 6. Time of the start of the $T = 10$ year monitoring period in which the locally-derived adaptation-threshold (AT) and its early signal and trigger (table 1), are expected to be reached. For strongly tide-dominated sites, to derive signals and triggers whose uncertainty windows are clearly separated in time, requires setting a higher adaptation-threshold than used in NZ. Conversely, in surge-dominated environments the severe consequences of large surge events suggests lower adaptation-thresholds than for NZ (table 1), allowing timely signals and triggers to be developed.

tolerable); financial or economically-based (e.g. insurance withdrawn or unaffordable, inability to raise a mortgage, disruption to business); culturally-based (e.g. access to cultural resources for food or materials, disruption to cultural events) depending on the socio-economic and/or cultural context e.g. [15, 18].

We have shown (figures 4, 6) that the same variable of interest, total storm-tide water level in our case, can be used to develop not only adaptation-thresholds, but also signals and triggers for pathway change before those thresholds are reached. The concept of monitoring for frequent occurrences of relatively small events to signal the approach of frequent large events, could in theory be applied to adaptation-thresholds for other climate-change problems, such as river flood discharges for example. However, whereas SLR is driving an ongoing, observable increase in the number of storm-tides reaching high elevations and its effect is relatively easily modelled [1–3], the effect of climate-change on river flood discharge is harder to detect—Haasnoot *et al* [18] therefore concluded that non-extreme variables such as average river flows might provide a more easily observable climate signal from which to develop signals, despite being somewhat de-coupled from the sequencing of high discharge events. Our method could be applied to other climate-change impacted variables such as river flooding, after first applying some form of climate-change scaling with time of the extreme flood distribution [17]. The method includes the full probability space, so in theory it represents all possible scenarios from a transient-scenarios approach to adaptive planning like that of Haasnoot *et al* [18], and provides the probable spread of timing of signals. It could therefore indicate the probability of false warnings, or of triggering adaptation too late.

While our study advances approaches for adaptive planning it does have some limitations. Like most other studies we have relied on the historical storm-tide distribution, since future projections are not well resolved yet e.g. [1, 4, 8, 10, 28, 31, 40]. Whereas a change to more frequent storm-tides on average, would hasten the onset of thresholds [4, 31], and vice versa, sensitivity tests (supplementary information) showed that increasing uncertainty in storm-tide distribution (with median unchanged) would increase the width of the uncertainty time windows, but have minor effect on the timing of thresholds. We have focused on sea-level height exceedances as the variable of interest for designing adaptation-thresholds, but other factors such as the duration or intensity of coastal flooding are also important to hazard exposure e.g. [50], and could be considered. We have also considered only storm-tides and SLR, but other processes such as rainfall, river discharge and waves also combine to contribute to coastal flooding in some locations, and would require joint-probability analysis to determine the likelihood of occurrence [2, 40, 51]. We have considered only the likelihood of physical hazard exposure, but have not considered socio-economic risk for which shared socio-economic pathways are being applied in our continuing research e.g. [8, 18, 52], or political indicators and triggers [25]. However, an advantage of adaptive planning is that the choice of adaptation-threshold can be made by communities considering locally-relevant socio-economic and environmental values linked to hazard scenarios; the method used here can then be applied to design a robust set of signals and triggers accordingly.

5. Conclusions

DAPP is emerging as a fit-for-purpose approach for adaptive planning to avoid the consequences of deeper and more frequent flooding with rising sea levels (or of other hazards), by identifying adaptive actions (pathways) that can avoid undue harm and increasing adaptation costs. Signals and triggers are critically needed to inform decisions on when to switch pathways to manage coastal-hazard and SLR impacts.

We used total storm-tide water level to design signals and triggers for pathway change. The new method frames storm-tide frequency in terms of probable timing of the number of events that reach a specific height threshold within a set monitoring period. This framing is well suited to adaptive planning, because it allows an exact and foreseeable period over which to monitor threshold exceedances to be specified, and thus to signal situations or trigger decisions on adaptive actions in time to avoid adaptation-thresholds. The method allows design of signals and triggers relative to the onset of an adaptation-threshold, thus accounting for the probable range of timing to indicate the probability of premature warnings or triggering adaptation too late. It provides an essential element to support the implementation of adaptation in changing climate and uncertain socio-economic conditions.

The steepness of the extreme tail of the sea-level distribution controls the timing of high sea-level thresholds (at present-day MSL) being reached after a period of SLR. The urgency to adapt is greatest for sites vulnerable to tide-dominated flooding, where the threshold for frequent damaging events will be reached earlier and for relatively small SLR, due to flat upper sea-level distribution. Conversely, sites that are presently adapted to high storm-surge-related thresholds, with steep upper sea-level distributions, will have more time to adapt to rising sea levels.

The spread of probable timing shows that if based purely on the physical hazard, it will be difficult to choose a signal or trigger that we are confident will occur before the adaptation-threshold but will not occur decades before the adaptation-threshold. Therefore, development of signals and triggers based on coastal-hazard considerations will need to be complemented by signals and triggers from different types of social, cultural and economic indicators, to reflect the many drivers of change and relevance to community perceptions of vulnerability and to enable decision makers to implement adaptive actions.

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