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Evaluating the fate of freshwater lenses on atoll islands after eustatic sea-level rise and cyclone-driven inundation: A modelling approach

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ABSTRACT

Dispersed human populations inhabiting remote atolls across the tropical Pacific Ocean are reliant on the viability of thin freshwater lenses (FWLs) contained within the island coralline sediments for their survival. Yet FWLs are uniquely fragile and easily damaged by saline intrusion. Eustatic sea-level rise (SLR) and sea flooding generated by intense tropical cyclones therefore pose special perils for continued existence on atolls. In this work, mathematical modelling is used to examine the effects on an atoll freshwater lens of various projected long-term SLR scenarios (10, 20, and 40 cm). A cyclone-driven wave washover event is then simulated in order to observe the responses and recovery of the FWL, subsequent to the SLR scenarios imposed. A key attribute of our model design is the inclusion of a topographic depression containing a low-lying fresh swamp in the atoll islet interior (which is often ignored), where seawater accumulates during inundation. Results indicate that a 40 cm SLR produces a major impact: the FWL decreases in thickness by approximately 50%, develops a brackish centre and contracts to a shrunken 'doughnut' morphology. Following cyclone inundation, observed salinity profiles are illuminating. Steep salinity gradients show how a strong saline plume forms at shallow depths, but also reveal the existence of an undisturbed fresh horizon beneath the salt plume under both present conditions and the modest 10 cm SLR scenario. Within the preserved fresh horizon, salt concentrations are maintained below 1.5 g/L (i.e. within usable limits) for at least a year. In contrast, the diminished freshwater lenses that exist after 20 and 40 cm SLR then exhibit far less resilience to saline damage over comparable post-cyclone timeframes. The findings point towards Pacific atolls becoming increasingly uninhabitable long before their complete submergence by sea-level rise, owing to irrecoverable groundwater salinisation seriously reducing the availability of freshwater.

1. Introduction

1.1. Pacific atolls: harsh environments

The dispersed and remote atolls of the world's tropical oceans are impressive biogenic landforms, rings of living coral reef attached at depth to sunken volcanic edifices (Nunn, 2010). Most atolls occur in the low latitudes of the central Pacific across Micronesia and Polynesia, and owe their modern configurations to eustatic and hydro-isostatic controls on palaeosea-level heights across the tropical Pacific during the Holocene (Dickinson, 2004). Accumulations of coralline sand and gravel washed up above high-tide level by wave action form small islets on top of these carbonate platforms. Known as *motu* throughout the Pacific, the separate islets[2] may be small and elliptical, or narrow but elongated along the atoll reef (McLean and Hoskin, 1991). From an outsider's perspective, the natural environment of atoll islands may appear idyllic, resembling exotic notions of 'paradise islands' portrayed by the tourist industry. But appearances are deceptive and the reality is that life on atolls is both harsh and precarious owing to environmental constraints on agricultural productivity and economic development. Available land on atolls is scarce and their carbonate soils are deficient in nutrients and extremely porous. Terrestrial ecosystems on atolls are therefore 'cool spots' with restricted biodiversity. Natural climatic variability also brings extended periods of drought (White et al., 1999) and occasional severe storms for those atolls lying in the tropical cyclone belts (Terry, 2007; Terry and Thaman, 2008).

Probably the greatest impediment for human inhabitation is the limited availability of freshwater, the only natural source besides rainwater occurring as thin groundwater aquifers contained within the sand and gravel substrate. These unconfined aquifers are known as freshwater lenses (FWLs) and are formed entirely by rainfall infiltration into the porous carbonate sediments. Density differences mean that FWLs 'float' hydrostatically on top of seawater below but the boundary is not sharp so the lens base is characterised by a wide transition zone of brackish water. Within FWLs, both flow and fresh/

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[2] In the context of atolls, the term 'island' is commonly used to mean the entire atoll configuration, upon which there may be deposited few or numerous individual sandy islets, sometimes lying tens of kilometres apart on opposite sides of the atoll lagoon. Islets may be small and elliptical, or narrow but elongate features along the reef top.

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seawater mixing occur mostly in a vertical rather than a horizontal direction (Underwood et al., 1992).

1.2. Multiple dilemmas: freshwater scarcity, sea-level rise and tropical cyclones

In spite of the challenges, Pacific Islanders living on atolls are tenacious people. They accept the harsh realities of their environments and have endured for thousands of years by following traditional subsistence lifestyles. Unfortunately, however, the future for continuing human occupation of atolls looks increasingly bleak. Some atolls are already facing serious difficulties associated with population growth: for example 40,311 people live in South Tarawa (15.76 km^2) in Kiribati (SPC, 2007), while tiny Ebeye (0.36 km^2) in Kwajalein atoll in the Marshall Islands has a population density exceeding 40,000 people/km^2. Problems stemming from such overcrowding pose major challenges for sustainability, with food security and water supply already under stress (Weir and Virani, 2011).

In this paper, the focus is on the vulnerability of freshwater lenses, which are uniquely fragile and easily damaged by human or natural disturbance (White et al., 2007a). Anthropogenic threats to lens viability include contamination by effluents, crop fertilisers or pesticides, for example leakage from household septic tanks or piggeries (Booth et al., 2008), while over-extraction can cause damage by upward seawater intrusion into the base of the lens (Diaz Arenas and Falkland, 1991; Dillon, 1997). Saline incursion can also occur by natural processes, including storm-wave washover during cyclones, as was observed on Pukapuka atoll in the northern Cook Islands after Cyclone Percy in 2005 (Terry and Falkland, 2010). Dry spells or longer periods of sustained drought (often ENSO-driven) diminish rainfall input and therefore reduce FWL recharge by infiltration (White et al., 1999; van der Velde et al., 2006; White et al., 2007b). During the 2011 drought in Tuvalu, for instance, severe water shortages on Funafuti and Nukulaelae atolls led to the declaration of a state of emergency and necessitated water rationing for several months. Modelling simulations suggest a FWL may take a year and a half to recover from drought (Bailey et al., 2009).

Furthermore, sea-level rise (SLR) is one of the most pressing concerns for atoll communities. It is ironic that atolls as geomorphic constructions owe their existence to the slow isostatic SLR accompanying subsidence of their volcanic foundations over millennial timescales, yet accelerated eustatic SLR in the current century due to global warming may well spell the demise of the reef-top islands through erosion and sediment removal (Nunn, 2010). At the same time, intolerance of many coral species sensitive to increasing ocean temperatures and ocean acidification may cause widespread die-out of corals in coming decades. Yet, arguably the most critical threat for continuing human habitation of atolls is associated with the likelihood of increasing groundwater salinisation. Future elevated sea levels will additionally place atoll FWLs at greater risk from wave washover during episodic tropical cyclones. Overall, an alarming picture begins to emerge of atoll islands becoming first uninhabitable and then eventually 'vanishing', with the consequent forced migration of atoll islanders as environmental refugees (Weir and Virani, 2011)

1.3. Aims

Against this background, continuing investigation is necessary to improve current understanding of atoll freshwater lens viability under various stressors. Therefore, the purpose of this paper is to explore the combined impacts of SLR and cyclone disturbance on atoll FWL conditions in the future. These aims build on previous work that examined the effects of storm-driven wave washover on FWL damage and recovery under static sea-level conditions (Chui and Terry, 2011). The current paper broadens the scope in three further stages. Stage 1 investigates FWL salinity responses under various long-term eustatic SLR projections. Stage 2 then examines the impacts of storm-wave washover after SLR has been imposed. Finally, stage 3 studies whether short-term temporary SLR associated with storm surge causes any additional impacts on FWL damage. A modelling approach is used, as described below.

2. Methods: numerical modelling techniques

2.1. Present scenario — undisturbed conditions

Numerical modelling methods are used to simulate the freshwater lens contained within the substrate of a tropical Pacific atoll islet. The initial model under current conditions with a static sea level is referred to as the 'present scenario'. Fig. 1A shows a cross section of half of an islet, from the middle of the islet to the ocean side, with an assumed symmetry about the left side of the diagram towards the lagoon side. The left side of the islet (not shown) thus extends to the atoll lagoon mirroring the right edge of the diagram, giving a total lateral extent of 1200 m for the islet. Our choice of 1200 m lies at the wider end of the size range typical of many atoll islets, but several reasons exist for making this choice. First, atoll islets with widths below about 400 m are too small to form viable freshwater lenses within them, so tend to be less populated and are therefore not relevant for this study. Second, the larger islets in an atoll configuration often support a significant proportion of the atoll population, owing to the greater land area available (with interior swamps) for food cultivation, so are more appropriate for study. Third, thicker freshwater lenses within bigger islets are generally considered to be more resilient to disturbance. Consequently, it is more pertinent to examine the impacts of SLR and storm-wave washover on more robust freshwater lenses, rather than studying the behaviour of much smaller lenses that may be easily affected by other types of environmental stressors, such as episodes of drought.

On the outer side of the modelling domain is the ocean, which is the source of salinity. The islet comprises two distinct substrates: hard cemented reef limestone at the bottom, upon which are deposited unconsolidated carbonate sands and gravels. Typical of atoll islets, the surface elevation above sea level of the loose sediments is just 2 m, reaching a maximum thickness of 7 m deep in their thickest section. An important attribute to highlight is that the surface topography in the model incorporates an 'inland' freshwater swamp in the interior of the islet. In order to evaluate atoll groundwater resources and assess their vulnerability to climate change, understanding the inherent geologic and topographic features is necessary (Nakada et al., 2011). Yet, although central low-lying depressions are a relatively common feature of atoll islet geomorphology (Rankey, 2011), they have largely been ignored in previous modelling investigations of atoll FWL behaviour. The accumulation of freshwater within these depressions makes them important sites for local people to grow staple food crops, in particular the giant swamp taro (*Cyrtosperma chamissonis*), common taro (*Colocasia esculenta*) and giant taro (*Alocasia macrorrhiza*) (Thaman, 2008). Parts of low lying freshwater swamps used for this purpose are known throughout the Pacific atolls as 'taro pits' (Manner, 2011).

The present scenario simulation is performed using the two-dimensional cross section domain illustrated in Fig. 2. The domain is discretized into a grid mesh containing 7360 individual rectangular elements in total. Along the middle of the bottom mesh boundaries are located the coarsest elements (height 2 m, width 25 m), while the finest elements occur along the bank of the interior swampy depression (height 0.04 m, width 0.56 m).

Similar to the technique described in Chui and Terry (2011), the simulations are performed using SUTRA. This is a numerical model developed by the U.S. Geological Survey for saturated–unsaturated variable-density groundwater flow with solute transport (Voss and

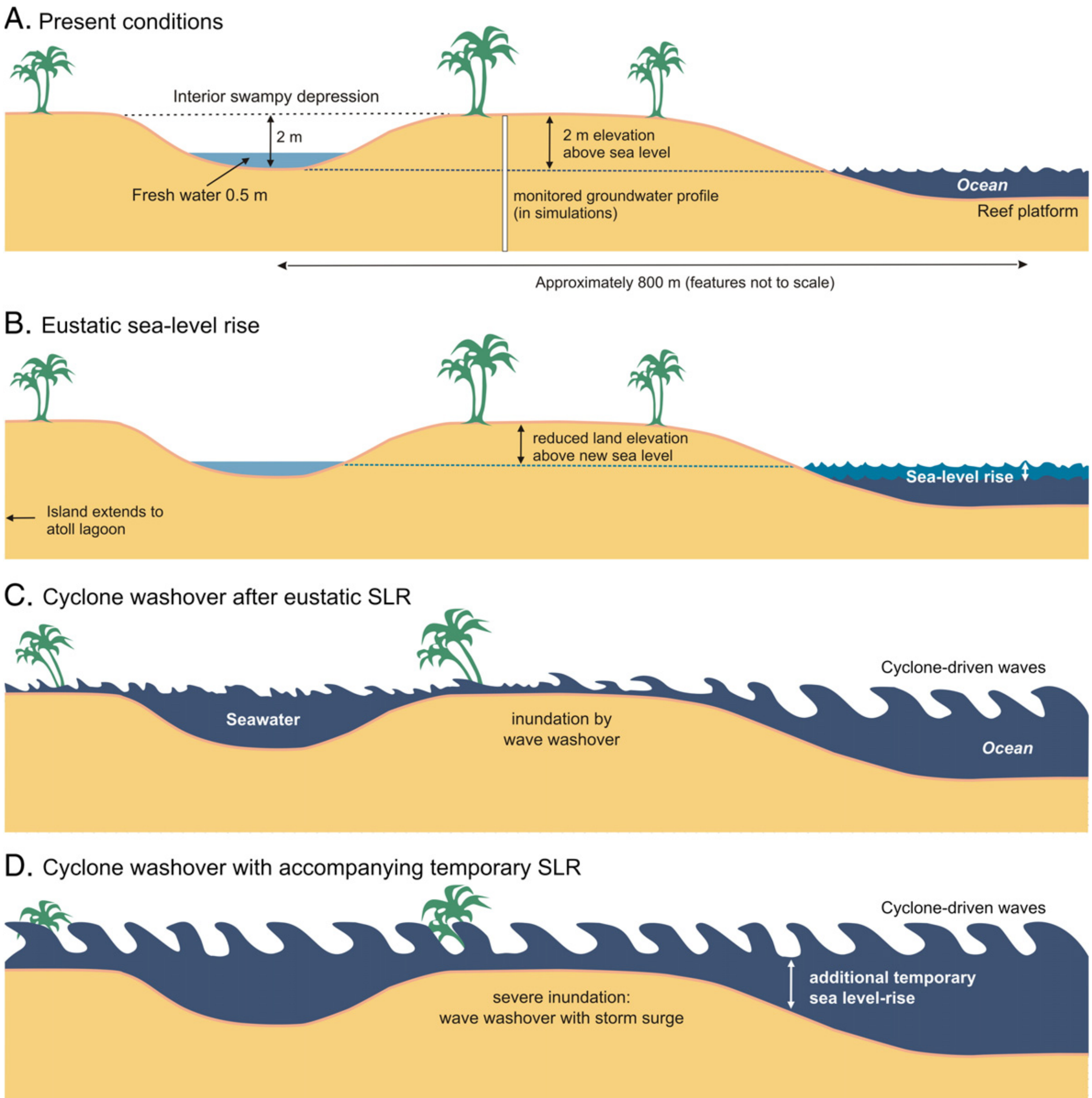

Fig. 1. Simplified and idealised configuration of an atoll islet used in modelling simulations of freshwater lens behaviour. The figure shows a cross section of half of an islet, from the middle of the islet to the ocean side, with an assumed symmetry about the left side of the diagram, going towards the lagoon side. The left side of the islet (not shown) thus extends to the atoll lagoon mirroring the right side of the diagram. Note the presence of the low-lying swampy depression towards the centre of the islet. The four images represent the following scenarios described in the text: A. present scenario for undisturbed conditions; B. future scenario after eustatic sea-level rise (SLR); C. inundation caused by wave washover during a future tropical cyclone event, after eustatic sea-level rise has taken place; D. another cyclone-generated inundation, but this time with an additional temporary sea-level rise (storm surge). In scenarios C and D, seawater fills up the interior swampy depression.

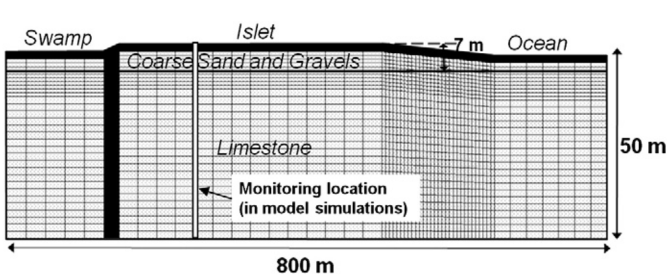

Fig. 2. Modelling domain, divided into a mesh of 7360 discrete rectangular elements, for performing simulations of groundwater flow and solute transport within the islet substrate. Along the surface of the domain and the bank of the inland freshwater swamp the mesh elements are very fine (0.04 m × 0.56 m), so they appear as thick black stripes.

Provost, 2008). The graphical pre- and post-processor for SUTRA is SutraGUI, run using Argus One software from Argus Interware, Inc. (Winston and Voss, 2004). Van Genuchten forms (van Genuchten, 1980) are employed for the retention and relative permeability functions. Parameters for unconsolidated sand from Laliberte et al. (1966) are applied to the coarse reef-derived sands and gravels. In contrast, the basement limestone is much more permeable than the overlying sediments. For simplicity, the parameters applied to the basement limestone are the same as for the carbonate sands and gravels above, except that the permeability is one order of magnitude higher. All the parameters adopted in the simulations are listed in Table 1.

A steady-state solution is first obtained to mimic the average present conditions conceptualised in Fig. 1A. Sea level is at 0 m, while the surface height of the freshwater contained in the interior swampy depression is 0.5 m. To represent rainfall input and lens recharge through infiltration, an inflow of 4 mm/day of rainfall is applied

Table 1
Model parameters.

Freshwater density [kg/m^3]	1000
Seawater density [kg/m^3]	1025
Freshwater salt concentration [g/L][a]	0
Seawater salt concentration [g/ L][a]	36.6
Depth of boundary between unconsolidated sands and gravels and basement limestone [m]	7
Permeability of sands and gravels — horizontal, vertical [m^2]	10^{-10}, 10^{-11}
Permeability of limestone — horizontal, vertical [m^2]	10^{-9}, 10^{-10}
Porosity [–]	0.42
Residual moisture content [–]	0.051
Van Genuchten parameters — α [m], n [–]	0.134, 9.0
Specific pressure storativity [ms^2/kg fluid]	9.0×10^{-9}
Fluid viscosity [kg/ms]	0.001
Change in fluid density with change in salt concentration (i.e.,$\partial \rho / \partial c$) [kg seawater/m^3·kg salt]	700
Longitudinal dispersivity — horizontal, vertical [m]	10, 1[b]
Transverse dispersivity [m]	0.1
Apparent molecular diffusivity of salt [m^2/s]	10^{-9}
Gravitational acceleration [m/s^2]	9.81

[a] 36.6 g/L is equivalent to 0.0357 kg salt/kg water, which is used for numerical modelling purposes, kg is used for consistency of units across related parameters.
[b] SUTRA supports the use of different longitudinal dispersivities for various flow directions to represent local anisotropy in a porous medium or aquifer structure, or the different sizes of heterogeneities experienced by flows in various directions. Refer to Voss and Provost (2008) for further details.

evenly over the islet surface. This corresponds to a mean annual rainfall of approximately 3000 mm with 50% loss through evapotranspiration. No flow crosses the left boundary due to symmetry. The right and bottom boundaries are also assumed to be no-flow. The boundary conditions for the salinity concentration are set at zero for freshwater and 36.6 g/L for the ocean. It is assumed that seawater salinity at the lagoon and ocean sides of the islet is equivalent. Rainwater accumulates to a depth of 0.5 m in the inland swampy depression. During simulations freshwater is maintained in the swamp for simplicity (i.e. zero salt concentration), unless the islet is inundated by seawater during a tropical cyclone (Fig. 1C and D).

The simulation for the present scenario (shown in Fig. 3) thus intends to capture the conventional features of FWLs on atoll islets in the tropical Pacific Ocean (see Chui and Terry, 2011 for more details). It also serves as a reference for imposed scenarios of sea-level rise and storm inundation of atolls (next section). The top of the FWL (i.e. the water table) under normal conditions rises above sea level close to the land surface, while the freshwater extends downwards several metres into the atoll substrate. The lens morphology is thickest inland, but thins out towards the coast at the edge of the islet. At the base of the FWL lies a broad transition zone where the freshwater gradually mixes with the seawater beneath. Our reference simulation therefore conforms to undisturbed FWL conditions typically observed on atolls.

2.2. Future sea-level rise and cyclone inundation scenarios

The investigation is pursued in three stages. The first stage is to impose various sea-level rises in order to investigate how the FWL is affected by long-term gradual eustatic change (Fig. 1B). Three steady-state SLR scenarios were chosen for simulation: 10, 20 and 40 cm rises. Although it is difficult to predict with certainty the time horizons over which such rises in sea level might occur, based on 3.1 mm/yr global average SLR from satellite altimetry measurements over 1993–2003 (IPCC, 2007), further rises of 10, 20 and 40 cm may be anticipated within the next 32, 65 and 130 years respectively. However, tropical Pacific regional eustatic SLR trends from 1993 to 2011 are faster than global rates (see BoM, 2011), giving 10, 20 and 40 cm rises within 20, 40 and 80 years respectively. These are clearly much shorter timeframes and therefore more alarming for Pacific atoll communities.

Stage 2 of the simulations next performs a series of transient runs, designed to simulate impacts of a future seawater inundation event, where an atoll is washed over by high waves generated by a tropical cyclone (Fig. 1C). This cyclone-driven inundation occurs subsequent to the three SLR scenarios described above. Post-inundation FWL recovery, if any, brought about through freshwater recharge over time, is also assessed. Not all Pacific atolls are affected by tropical cyclones, only those that lie within the cyclone belts approximately 10°–20° north and south of the equator. Yet, while it is true that atolls close to the equator (e.g. those in Kiribati) do not experience cyclones, severe storms do occur on occasion, which feature waves washing across the islets, although perhaps for shorter times and with shallower inundation depths than modelled here. For atolls that have experienced an intense cyclone passing in close proximity, storm-wave washover typically lasts between 1 and 3 h (Terry, 2007). However, even as a cyclone then moves away along its migratory path, seawater continues to pond on saturated low-lying ground, such as in interior depressions and other hollows. The surface detention of seawater typically experienced after inundation is another important reason for incorporating the topographic depression feature in our model.

The steady-state solution obtained in Fig. 3 ('present scenario') is used as the starting point or initial condition for performing these simulation runs. The figure shows the lens beneath half of the islet, from the middle of the islet to the ocean side, with an assumed symmetry about the left side extending towards the lagoon side. To simulate the combined effect of wave overtopping and subsequent ponding, seawater at the concentration of 36.6 g/L is assumed to inundate the entire atoll for 10 h. This represents 2 h of storm-wave washover, followed by a further 8 h of subsequent ponding time for seawater that cannot infiltrate quickly once the ground becomes saturated. Seawater also fills up the freshwater swamp, which therefore becomes completely saline for an equivalent duration. To simplify modelling of the swamp, a hydraulic head of 2.0 m is applied

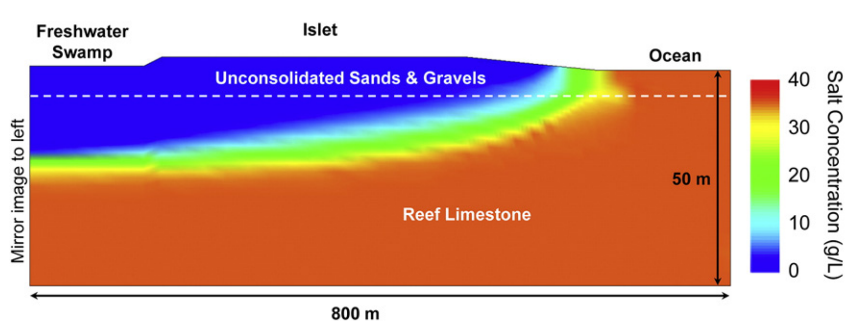

Fig. 3. Simulation of salinity distribution within an atoll freshwater lens under present undisturbed conditions ('present scenario'). The freshwater swamp (low-lying depression) is located towards the middle of the islet (i.e. the image is mirrored on the left side with an assumed symmetry to extend across the reef foundation to the atoll lagoon).
Based on Chui and Terry (2011).

during the 10-hour inundation (to represent seawater accumulation), but is brought back to the pre-storm value of 0.5 m immediately afterwards. Similarly, infiltration into the substrate beneath the swamp is assumed to be completely saline during the entire 10-hour duration of inundation, but completely fresh afterwards. After the 10-hour event, other boundary conditions revert back to pre-storm conditions. Freshwater infiltration of 4 mm/day is applied over the land surface for a further 1 year, in order to monitor the ability of the FWL to recover from saline damage. Throughout the recovery period, the tidal range is assumed to be minimal and sea level is maintained at the relevant SLR scenario, i.e. 10, 20 or 40 cm above the present scenario. The initial time step at the start of the 10-hour inundation event is 0.1 s, increasing to a maximum time step of 60 s. During the simulation of subsequent recovery, the initial and the maximum time step are 0.1 s and 2 h, respectively. The time-step multiplier in both cases is 1.02 for every time step, until the maximum time step is reached.

Finally, stage 3 examines whether or not the temporary sea-level rise, occasionally experienced during very intense tropical cyclones because of storm surge, has any additional effect on FWL damage above that experienced in stage 2. Storm surge is a short-lived SLR produced by a combination of deep low pressure near the centre of a tropical cyclone and strong onshore winds pushing water against a coastline if a favourable track alignment occurs. Not all coastal locations are affected by significant storm surge during cyclones because offshore bathymetry, coastline configuration (whether or not a coastline is indented with bays or estuaries that allow funnelling of surge waters) and timing with respect to high tide, are other influencing factors. Nonetheless, past strong cyclones with central pressure dropping below 950 hPa have been known to generate devastating surge, on top of which are driven immense storm waves (Fig. 1D). In this final stage of analysis, two further simulations are run, but with an extra 2 and 4 m of temporary SLR imposed for the first 2 h of the total 10-hour event, i.e. short-term SLR only during the period of inundation while the cyclone track passes close to the atoll. These simulations are performed on the present scenario, i.e. for current eustatic sea-level position.

3. Results

3.1. Stage 1: freshwater lens responses to eustatic sea-level rise

How the atoll islet freshwater lens responds to various scenarios of long-term eustatic sea-level rise can be assessed by examining the evolution of the salinity profiles in the top 20 m of the aquifer. Since the tidal range is assumed to be minimal and the simulations are steady state, they do not indicate or try to account for the time taken for horizontal salt dispersal through permeable islet substrate, but instead show the final outcome in terms of groundwater salinity patterns. A set of cross sections through the FWL to demonstrate the results is given in Fig. 4. The individual sections illustrate the FWL beneath half of the islet, from the middle of the islet to the ocean side, with an assumed symmetry about the left side extending towards the lagoon side. There are several features of the lens responses that stand out in particular when comparisons are made with the ‘present scenario’ representing no sea-level rise.

For the 10 cm SLR scenario the shape and thickness of the main body of the FWL is largely unaffected. The transition zone of brackish water (bands of green and yellow colours) that separates freshwater from seawater at the lens boundary thickens slightly both beneath the swampy depression in the centre of the islet (left side of image) and at the ocean margin (right side of image). With 20 cm of SLR these peripheral changes are similar, although slightly more pronounced. More notable, however, is that the overall thickness of the FWL decreases by approximately 20–25%. Additionally, the water quality of the aquifer beneath the central swamp changes from being completely fresh (initially dark blue colour, salt concentration close to 0 g/L) to slightly brackish (light blue, 5–10 g/L).

As might be anticipated, the strongest effects on the FWL are experienced after the 40 cm SLR scenario is imposed on the atoll island. In all the scenarios, freshwater seeps down from the central swamp because hydraulic pressure from the swamp (with its surface 0.5 m above sea level) is always higher than the pressure from the sea. However, in the 40 cm SLR scenario, the difference in the pressure becomes so small that the freshwater seeping from the swamp is not enough to work against the seawater intruding from the ocean. In response, an up-coning of brackish water is therefore observed beneath the swamp, such that the salt concentration of the groundwater increases uniformly to about half that of seawater (green colours, about 20 g/L). Consequently, the zoomed section of the image at the bottom right in Fig. 4 shows that freshwater no longer exists in the middle portion of the lens. Elsewhere in the FWL, outside the central topographic depression, the original thickness of the freshwater horizon (blue colours) reduces by approximately 50%, signalling a marked reduction in available water resources. In the two dimensional view illustrated, these changes combine to give the appearance that one large continuous FWL becomes divided into two small pockets of freshwater on either side of the islet's interior topographic depression (one shown, one in the mirror image to the left). The width of the new central brackish zone dividing the FWL corresponds roughly to the width of the topographic depression above it. However, to fully appreciate the 3-dimensional form

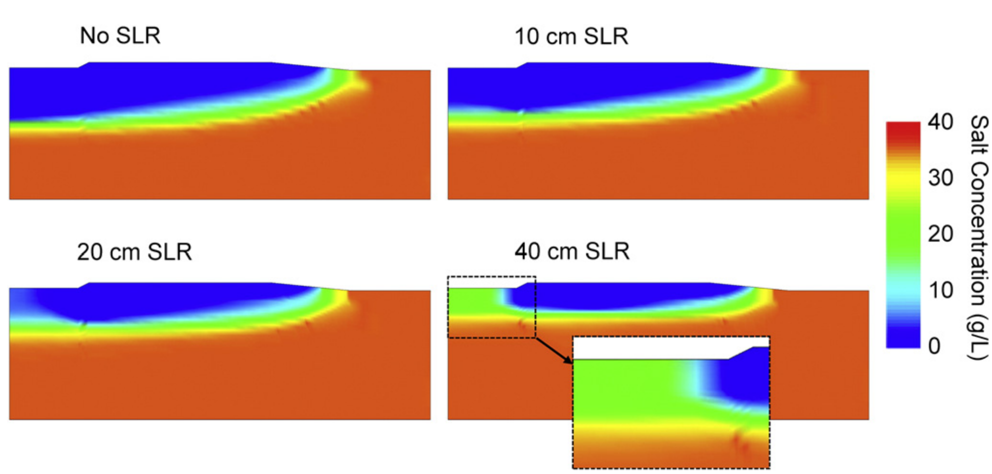

Fig. 4. Comparison of present scenario (no sea-level rise) against simulations of various projected long-term eustatic sea-level rises (SLR), showing the corresponding responses of salinity distribution in the atoll freshwater lens profiles. The separate images are mirrored on the left with an assumed symmetry to extend across the reef foundation to the atoll lagoon. Horizontal and vertical dimensions are as shown in Fig. 3.

of the affected FWL, it is necessary to rotate the image through 360° 'into the page'. Rotation reveals how the morphology of the original FWL, previously thickest in the centre, has significantly diminished to a thin 'doughnut' of freshwater surrounding a central brackish zone.

Finally, although investigation of the relationships between atoll islet size and freshwater lens responses to sea-level rise deserves a detailed consideration, this work lies beyond the scope of the present paper. Nonetheless, as a check that the results presented above are not an artefact of the relatively broad islet (1200 m) chosen here for modelling, steady-state simulations were repeated for the 0 and 40 cm SLR scenarios on a narrower atoll islet of total width ~750 m, i.e. half the size. Importantly, it was found that this much narrower islet still supports a freshwater lens (although the dimensions of the lens are proportionately less than in the original scenarios above) and the general behaviour of the lens to SLR is similar to the findings above. In particular, the doughnut morphology again develops on the smaller FWL after the 40 cm SLR is imposed.

3.2. Stage 2: post sea-level rise freshwater lens responses to cyclone-driven wave washover

Any projected eustatic sea-level rise affecting atoll islands in the future will also increase vulnerability of the islands to inundation by wave overtopping during tropical cyclones, with associated geomorphic and hydrological consequences. Recent studies that relied on field observations and model simulations have demonstrated that even at present sea levels, cyclone-generated wave inundation of atoll islets causes saline damage to freshwater lenses (Terry and Falkland, 2010; Chui and Terry, 2011). Such damage requires at least a year for recovery or longer, depending on various parameters related to post-storm environmental conditions. In the present study, the second stage of investigation examines how atoll FWLs respond to a future cyclone-induced wave washover event, after the long-term sea-level rise scenarios described in the previous section have been imposed.

Fig. 5 displays the FWL responses at the simulated monitoring position (i.e. 250 m from the left of the domain shown in Fig. 2) at various time horizons with respect to a future tropical cyclone wave washover event. The chosen time horizons are (1) before the cyclone, (2) immediately after the storm, (3) 2 months post-storm and (4) after 1 year of recovery. Two sets of comparisons are possible from the data. Inspection of an individual graph indicates the FWL response at the selected time horizon, according to whether the cyclone washover occurred under the 0, 10, 20 or 40 cm long-term eustatic sea-level rise scenario. Comparison between the graphs shows differences through time in the ability of the FWL to recover from the wave inundation under these SLR scenarios.

Fig. 5A indicates conditions before the impact of a tropical cyclone event. It is seen that the surface (i.e. water tables) and top portion of the freshwater lens under all sea-level rise scenarios is fresh to depths of at least 5 m. Beyond 5 m depth the salinity lines diverge owing to the variations in projected FWL thickness under the four SLR scenarios. The upper tolerance of salt concentration in water for human consumption is approximately 1.5 g/L (George et al., 1996). This value is higher than the WHO guideline value for drinking water of 0.25 g/L (WHO, 2006), but reflects the reality that water with higher than aesthetic (taste) salinity preferences is commonly used for domestic purposes on Pacific atolls in the absence of alternative supplies. Using the 1.5 g/L limit as the salt concentration value to define the base of the freshwater lens, it is seen that under the 10 and 20 cm SLR scenarios the FWL base is not reached until 13–14 m depth. In contrast, freshwater extends only to a depth of 9 m under the 40 cm SLR scenario.

Immediately after the tropical cyclone event causes wave washover across the atoll islet (Fig. 5B), significant responses develop in the FWL. At the aquifer surface, an almost identical impact is felt under all four SLR scenarios. The water table (0–2 m) becomes so saline that the lines on the graph extend beyond the upper limit of the x-axis, i.e. greater than 14 g/L. However, salinity then decreases rapidly with depth in all cases, such that water quality improves to within usable limits (1.5 g/L) by a depth of between 2 and 3 m. Below this depth it is seen that an undisturbed fresh horizon exists, which extends to the base of the FWL. Thus, in spite of the salinisation that occurs in the near-surface portion of the lens due to saline intrusion, a zone of freshwater remains preserved within the aquifer. This fresh horizon exhibits different thicknesses according to which SLR scenario has been imposed prior to the cyclone event: present scenario (no SLR) — 11 m thick; 10 cm SLR — 10 m thick; 20 cm SLR — 8 m thick; 40 cm SLR — 6.5 m thick.

Fig. 5C illustrates the continuing effects of the saline intrusion 2 months post-cyclone. Over the 2 month period, there is assumed to be 4 mm/day of freshwater infiltration from rainfall. An equivalent strong recovery is seen at the aquifer surface for all SLR scenarios, although salt concentrations still render the groundwater unusable

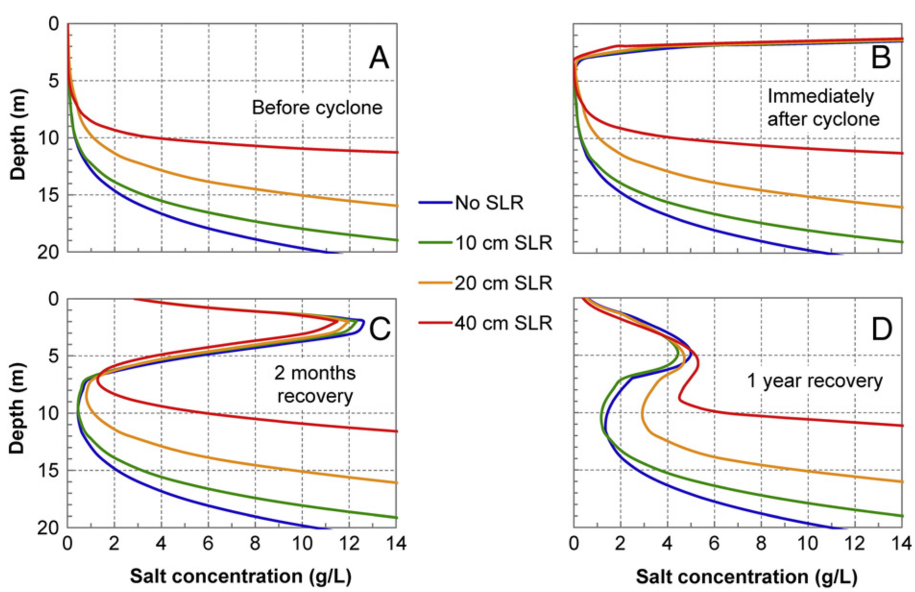

Fig. 5. Salinity profiles through an atoll island freshwater lens at monitoring position (see Fig. 2), at selected time intervals before and after a cyclone-generated wave washover event. Model simulations are run after four scenarios of eustatic sea-level rise (SLR) have been imposed: 0, 10, 20 and 40 cm (see text for details).

(>3 g/L) immediately below the land surface. Below this, a salt plume has developed with a similar shape and concentration characteristics for each SLR scenario. The plume has a maximum salinity of 11.5–12.5 g/L at about 2 m depth in all cases. Beneath the salt plume, however, the fate of the sandwiched freshwater horizon differs. Under no-SLR and 10 cm SLR scenarios (blue and green lines) the response is similar: the thickness of the preserved fresh horizon (<1.5 g/L) remains relatively substantial, extending from 7 to 13–14 m deep (i.e. 6 to 7 m thick). Under the 20 cm SLR case (orange line) the top of the fresh horizon is also found at a similar depth (7 m) but is only 4 m thick. The situation is worst under the 40 cm SLR scenario (red line). Here, a fresher layer still exists, but that part with salinity<1.5 g/L is much reduced, now less than 2 m thick. Overall this indicates that although partial recovery from salinisation is felt at the water table, the salt plume produced at depth by wave washover infiltration has the biggest impact following a 40 cm eustatic rise in sea level. This is a consequence of the much thinner condition of the FWL at the start of the wave washover simulation, following the higher SLR scenario.

A full year following the cyclone washover event (Fig. 5D), the dynamics of freshwater lens recovery again exhibit variation between the suites of different SLR scenarios imposed. At the top of the aquifer, from just below the ground surface to 1 m, the patterns are mostly comparable, since water quality has improved in all cases to within usable limits (<1.5 g/L). Continuing downwards through the FWL, the salinity profiles remain consistent across all SLR scenarios. The gradients of salinity increases with depth are equally steady, and notably less steep than in Fig. 5C, indicating how the upper lens profiles benefit in a similar fashion to freshwater recharge by annual rainfall. For the same reason, between 2 months and 1 year the position of the salt plume has migrated downwards by about 2.5 m to a new depth of between 5 and 6 m. Although maximum salinity of the salt plume has diminished, it is observed that the highest plume concentration exists under the 40 cm SLR scenario (red line).

Sandwiched beneath the salt plume and the base of the FWL, the preserved horizon of fresher water is still evident after 1 year in some cases. For the no-SLR and 10 cm SLR scenarios (blue and green lines), this horizon has experienced only slight increases in salinity over the last 10 months. By far the most obvious profile changes are observed under the 20 and 40 cm SLR scenarios (orange and red lines), where mixing with the salt plume above has caused notable salinity rises in the fresher horizon, to new minimum values of 3 and 4.5 g/L, respectively. Indeed, for the 40 cm SLR case, the freshwater horizon has almost completely dispersed, with the salinity profile now showing a more or less continuous increase in salt concentration down through the FWL, except for a hiatus between 6 and 9 m deep where salinity stabilises at 4.5–5.5 g/L. The main finding here is that FWL disturbance by cyclone-generated saline intrusion is much more pronounced after 20 or 40 cm of eustatic sea-level rise. In both cases, even after a year of recovery no fresh groundwater resources exist except in a shallow layer just at the water table.

3.3. Additional temporary sea-level rise due to storm surge

The third and final stage of the investigation involved modelling the behaviour of the freshwater lens immediately after wave inundation of the atoll islet, but incorporating an additional temporary sea-level rise from storm surge during the passage of the cyclone. Two storm surge heights were simulated, representing short-term SLR of 2 and 4 m above current eustatic sea level, to compare with wave washover effects in the absence of a storm surge component. Fig. 6 illustrates the perfect alignment of the three resulting graphs, indicating no difference in the immediate post-cyclone salinity profiles. A discernable effect was noted in the case of the 4 m temporary SLR (i.e. 2 m deep inundation over the land), but only for the initial 10–30 min into the storm. During this early period,

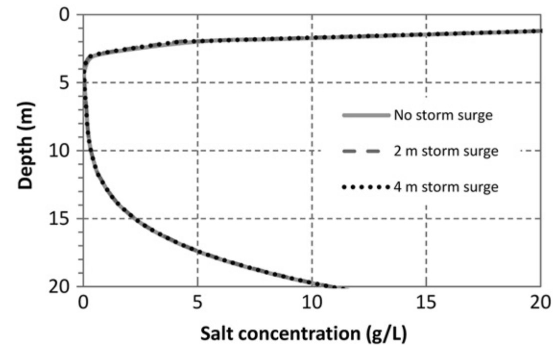

Fig. 6. Salinity profiles through an atoll islet freshwater lens at monitoring location immediately after disturbance caused by cyclone-generated seawater inundation. The solid line indicates the effect of wave washover alone, while the dashed and dotted lines include an additional storm surge component (i.e. short term sea-level rise).

the additional depth of seawater over the land infiltrates and damages the freshwater lens more quickly compared to the other temporary SLR scenarios, resulting in differences in the saturation and salinity curves between 10 and 30 min (not shown). Once the vadose zone is filled with seawater, however, any additional depth of water above the land surface produces minimal additional impact. Thus, the key finding here is that maximum saline damage to the FWL is produced by wave washover alone, while more severe (i.e. deeper) flooding across the atoll produced by simultaneous temporary storm surge does not worsen the overall situation further.

4. Discussion

Coastal impacts associated with greenhouse-driven sea-level rise potentially threaten all Pacific Islands, but low-lying atoll islands clearly face a particular peril (Dickinson, 1999; Church et al., 2006). Even if radiative forcing of climatic change is stabilised by emission control, global SLR is projected to continue for several centuries (Jevrejeva et al., 2012). As well as eustatic causes, many atolls experience faster rates of submergence owing to the additional effect of downward isostatic motion (subsidence). On Funafuti atoll for example, over 1950–2009 the combined rate of submergence and subsidence is 4.5–5 mm/yr (depending on method of estimation), or about three times the global mean rate of SLR (Becker et al., 2012). Although it is certainly the case that some other atolls are rising due to tectonic effects, this kind of information helps to create the images of atoll islands possibly 'vanishing' during the 21st century that have captured world-wide attention. But in spite of these alarming scenarios, scientific debate on how accelerated SLR might erode the sedimentary fabric of atoll islands has not yet reached consensus. Woodroffe (2008) suggests that variations in topography, emergence features and substrate stability will influence the susceptibility of individual islets to SLR. More recent detailed work by Webb and Kench (2010) indicates that for 86% of the atolls they investigated in the central Pacific, the total 'land' area (i.e. the combined area above high tide of all the islets making up an atoll) stayed steady over the past 2 to 6 decades. Some islets lose area and others gain, but even for those that remain the same area, there is often movement of land (sand) from one end to the other of that islet.

Yet, in terms of continued human occupation of Pacific atolls, such discussions may be of secondary importance within the broader script of environmental sustainability. For even if some islets demonstrate physical resilience, this study has illustrated that the morphology, thickness and resilience (and therefore long-term viability) of their freshwater lenses will be reduced by rising seas. Therein lies the rub: before atoll islands begin to show any major decline in overall size, they may nonetheless be rendered increasingly uninhabitable by the relentless diminution of available water resources. For many remote atoll communities, the availability of clean, potable freshwater is already a major challenge for public health, especially as overcrowding on some islets has long since reached critical levels (Spennemann, 2006; White et al., 2008; White et al., 2010). Subsistence cultivation is similarly hampered: groundwater quality in taro pits monitored across the atolls of Tuvalu between January and April 2006 by SOPAC[3] (Webb, 2007) revealed that salt concentrations in some pits on Nukulaelae, Niutao and Funafuti are already too high for successful swamp taro growth, while the interior swamps of Fongafale islet repeatedly experience problems of saline flooding by spring tides (Yamano et al., 2007).

On top of these long-term SLR effects, the known adverse impacts of tropical cyclones on diminished groundwater resources will then become more serious, as demonstrated by our findings. Although many issues remain unresolved concerning the association between rising sea-surface temperatures and both the incidence and intensity of tropical cyclones, especially in the South Pacific context (Walsh, 2004; Terry and Gienko, 2010), occasional anomalous episodes and El Niño periods have both been identified as spawning more cyclones east of 180° (Chu, 2004; Terry and Etienne, 2010). This implies that the observed shift towards a more El Niño-like state in the South Pacific over recent decades (Walsh et al., 2012), if continuing into the future, might advent a heightened risk of storminess to the atolls of Tuvalu, Tokelau, the Cook Islands and French Polynesia (i.e. near to and east of the dateline). Consequently, more frequent episodes of severe saline damage in the aftermath of cyclone-driven wave washover of atoll islands may not allow freshwater lenses to recover fully before a subsequent inundation event occurs, leading to sustained and possibly irreversible groundwater salinisation.

5. Summary and conclusions

In this study, a mathematical modelling approach was used in stages to examine the responses of a Pacific atoll freshwater lens to long-term sea-level rise and short-term storm-induced disturbance. Three eustatic sea-level rise scenarios (10, 20 and 40 cm) were imposed for comparison with current conditions, followed by simulation of saline damage caused by wave washover of the atoll during a tropical cyclone. A key attribute of our model is that its design incorporates the typical topographic feature of larger atoll islets previously ignored in atoll groundwater modelling research, i.e. an inland low-lying depression (freshwater swamp) where seawater collects during wave inundation. The principal modelling results are as follows:

(1) A 10 cm SLR results in relatively minor change in FWL configuration and thickness. However, a 40 cm SLR reduces the familiar lens morphology into a doughnut shape, which is approximately 50% thinner and develops a brackish centre. The low-lying depression in the islet interior is the feature most closely associated with these transformations.

(2) Assessment of salinity profiles illuminates the main FWL responses to cyclone-induced wave washover. As expected, the water table (aquifer surface) suffers most from saline incursion. Strong near-surface recovery is observed after 2 months in a similar pattern across all SLR scenarios, although not to within usable limits.

(3) At shallow depths a saline plume forms within the FWL. Even after a full year of rainfall recharge, the plume does not fully disperse under all SLR scenarios.

(4) At greater depths within the aquifer, sandwiched between the saline plume above and the base of the FWL, an undamaged fresher horizon is preserved after cyclone-driven washover of the atoll islet. This horizon maintains salinity levels below 1.5 g/L (i.e. within usable limits) under the no-SLR and 10 cm SLR scenarios and remains intact for at least a year. In contrast, the diminished FWL configurations after 20 and 40 cm of SLR mean they exhibit far less resilience to subsequent saline damage caused by storm-wave washover.

Implications of these findings are that sustained and possibly irreparable freshwater lens damage by cyclone-generated wave washover of affected atoll islands should be increasingly anticipated under projected scenarios of sea-level rise. This is because sea level-rise causes a freshwater lens to change morphology, progressively diminish in thickness, demonstrate less resilience and exhibit slower recovery after disturbance. Consequently, it appears likely that Pacific atolls may become uninhabitable long before eustatic sea-level rise submerges them completely, owing to advancing groundwater salinisation limiting the availability of freshwater for consumption or growing food.

[3] Pacific Islands Applied Geoscience Commission, now the Applied Geoscience and Technology Division of the Secretariat of the Pacific Community.

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