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IMPACT AND ADAPTATION ASSESSMENT OF CYCLONE DAMAGE RISKS DUE TO CLIMATE CHANGE

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ABSTRACT

Increases in wind damage are expected if the intensity and/or frequency of tropical cyclones increase due to enhanced greenhouse conditions (climate change). The paper estimates cyclone damage risks due to enhanced greenhouse conditions for residential construction in North Queensland, and then assesses the economic viability of several climate adaptation (hazard mitigation) strategies. The analysis includes probabilistic modelling of cyclone intensity and frequency, time-dependent increase in wind speed from enhanced greenhouse conditions (global warming), and vulnerability functions of building damage. Increases in mean annual maximum wind speed from 0% to 25% over 50 years are considered to represent the uncertainty in changing wind hazard patterns as a result of climate change. The effect of regional changes to building inventory over time and space, rate of retrofitting, cost of retrofit, reduction in vulnerability and discount rate will be considered. The risk-cost-benefit analysis considering temporal changes in wind hazard and building vulnerability can be used to help optimize the timing and extent of climate adaptation strategies.

1. INTRODUCTION

Increases in wind damage are expected if the intensity and/or frequency of tropical cyclones increase due to enhanced greenhouse conditions (climate change). However, the 2007 Intergovernmental Panel on Climate Change (Christensen et al. 2007) provides very little guidance as to the expected increase in intensity and/or frequency of tropical cyclones in Australia and elsewhere. However, Walsh et al (2001) predicts up to a 25% increase in wind gusts for the same return period wind speeds for Townsville, Cairns and other coastal locations in North Queensland by 2050. Yet, a more recent report by the same author states that maximum tropical cyclone winds are likely to increase by only 5-10% by some time after 2050 (Walsh et al. 2002). A review of the most current research (AGO 2007) suggests that the most likely scenario is a 5-10% increase in wind speeds by 2050, with an increase of 25% being the worst-case scenario with a low probability that this scenario will eventuate. There is also the possibility that wind speeds will not increase at all due to climate change. Hence, the paper will consider a range of increases in wind speeds from 0% to 25% in North Queensland over the next 50 years, but most results will be presented for a 10% increase in wind speed as this appears to be the most likely scenario arising from enhanced greenhouse conditions.

Tropical cyclones and hurricanes can cause significant sources of economic loss, for example, Cyclone Tracy in 1974 caused over $500 million in damages (Holmes 2001), and Cyclone Larry in 2006 caused over $1 billion in damages. Approximately 60-80% of damage caused by Cyclone Larry arose from damage to residential construction in houses built before enhanced building standards were implemented in North Queensland from the early to mid 1980's (Ginger et al. 2007). The potential for larger losses exists given the increasing development of coastal communities in North Queensland.

Following the devastating damage caused by Cyclone Althea (Townsville) in 1971 and Cyclone Tracy (Darwin) in 1974 changes were made to the Queensland Home Building Code (1981) requiring new housing to be strengthened by a set of deemed-to-comply provisions (e.g. Walker 1980). These enhanced building standards for houses came into effect on 1 July 1982, although many new houses built in the years prior to 1982 complied to the Australian Wind Loading Code AS1170.2 (1989). This means that houses built since 1980-1985 in North Queensland represent 'properly engineered forms of cyclone resistant construction' (Reardon and Henderson 1998) – this enhanced type of residential construction is referred to herein as 'post-1980 construction'. Other related standards, such as wind loads for housing AS4055 (2006) and residential timber framed construction for cyclonic regions AS1684.3 (2005) are used in more recent housing design and construction. Hence, the vulnerability of pre-1980 construction is significantly higher than post-1980 construction.

If damage from cyclones is expected to increase with time due to climate change, then climate adaptation strategies may be needed. This may be achieved by retrofitting/strengthening pre-1980 construction to the enhanced post-1980 standard. Another climate adaptation strategy may be to further reduce the vulnerability of new construction, or to implement planning controls to limit development in highly vulnerable coastal locations. Most cyclone (hurricane) risk research has focused on changes to building vulnerability and inventory and its time-dependent effect on damage risk (e.g., Harper 1999, Granger et al. 2000, Huang et al 2001, Jain et al 2005). However, relatively little attention has been paid to quantifying the costs and benefits of climate adaptation strategies (retrofitting, strengthening) and assessing at what point in time a climate adaptation strategy becomes economically viable. Cost-benefit analysis for strengthening a residence to withstand cyclones has been used to weight different retrofit options on hazard mitigation (Li and Ellingwood 2009). Stewart et al. (2003) and Stewart (2003) developed a cost-benefit analysis decision-making framework to assess the economic viability of strengthened construction and other damage mitigation strategies for U.S. and Australian hurricanes and tropical cyclones. In this work, retrofitting was assumed to occur when cyclone damage occurred and so the additional cost of the retrofit was minimised (since the structure had to be repaired anyway) and since damage would occur to the most vulnerable construction then over a long time period it would be expected that the most vulnerable construction would be retrofitted, thus reducing the region-wide vulnerability to tropical cyclones.

A cyclone damage risk-cost-benefit analysis is developed to assess the economic viability of several climate adaptation (hazard mitigation) strategies. The effect of regional changes to building inventory, rate of retrofitting, cost of retrofit, reduction in vulnerability and discount rate will be considered. Three site exposures are considered: foreshore, town and inland. Results will be given in terms of annual and cumulative economic risks and damage loss. Given the uncertainty of the impacts of global warming a range of increases in wind speed are considered: (i) no climate change (stationary system) and (ii) mean annual maximum wind speed increases by 5% to 25% over the next 50 years (non-stationary system). A particular climate adaptation strategy will be economically viable when the cumulative costs of retrofit and reduced damages fall below the cumulative damage costs of existing vulnerability (i.e., ‘‘do nothing’’ scenario) - in other words, the net benefit of the climate adaptation strategy exceeds zero. The risk-based cost-benefit analysis considering temporal changes in wind hazard and building vulnerability can be used to help optimize the timing and extent of retrofitting existing houses to adapt to the potential impact of enhanced greenhouse conditions.

There is clearly great uncertainty and debate about predicted changes in wind hazards due to climate change and so it is not the intention of this paper to support any specific assumption of climate change. Instead, the purpose of this paper is to investigate the potential impact of assumed climate change scenarios on damage loss estimation and examine the cost-effectiveness of various climate adaptation strategies. This paper will provide important decision support information to building code and government planning agencies.

2. PROBABILISTIC WIND MODEL

Probabilistic wind field modelling of the North Queensland cities of Cairns, Townsville and Mackay has been conducted by Harper (1999) where the predicted wind speeds from Harper (1999) compare very well to measured tropical cyclone data, and that Cairns, Townsville and Mackay have similar extreme wind climates. Since most site specific simulation-based hazard models are proprietary and not available for this study, Stewart (2003) fitted an EV-Type I distribution to the Harper (1999) predictions. The EV-Type I (Gumbel) cumulative distribution function for annual maximum gust speeds is thus

$$F_v(v) = \exp\left[-e^{-\alpha(v-u)}\right] \quad (1)$$

where v is the gust wind speed (m/s) for a standard category 2 terrain (AS1170.2, 1989) and a 10 m anemometer height and the parameters u and α are site-specific. The statistical parameters are α =0.154 and u=13.60 for North Queensland (Stewart 2003). The parameters correspond to annual mean maximum wind speed of 17.4 m/s and coefficient of variation (COV) of 0.48.

If we assume a 10% increase in wind speed after 50 years then the annual mean maximum wind speed increases to 19.1 m/s. As there is no information how the increase will occur, a linear time-dependent increase in mean wind speed is assumed. The COV for wind speed for all years is assumed constant at 0.48. In this case, the Gumbel parameters u(t) and α(t) are time-dependent and so the time-dependent probability density function of the Gumbel distribution for annual maximum gust speeds is

$$f_v(v) = \alpha(t)e^{-\alpha(t)(v-u(t))}\exp\left[-e^{-\alpha(t)(v-u(t))}\right] \quad (2)$$

The probabilistic wind field model described herein is relatively simple but it will allow the relative changes in damage risks and losses due to temporal changes in wind hazard and building vulnerability to be estimated.

While the present study has focused on a known cyclonic region subject to assumed increases in wind speeds, another consequence of enhanced greenhouse conditions is the poleward shift of tropical cyclones (CSIRO 2007). A southern shift of 2 degrees of latitude is approximately 200 km, so regions historically not subject to cyclones may in the future be more vulnerable to damage. The incorporation of the poleward shift of tropical cyclones in the probabilistic framework developed herein is beyond the scope of the present report, but is clearly an area in need of further research.

3. BUILDING VULNERABILITY FUNCTIONS

A building vulnerability function relates wind speed to building damage, which in this paper is expressed in terms of percentage damage which can then be related to economic loss. Several vulnerability models for wind hazard have been developed (Unanwa et al. 2000, Khanduri and Morrow 2003, Pinelli et al. 2004, Jain et al. 2005). In Australia, a widely used building vulnerability model for North Queensland is that proposed by Walker (1994) based on insurance industry experience. The vulnerability function for insured damage to residential construction in North Queensland is summarised as (Stewart 2003):

$$F_D(v) = 20\left(\frac{K_t K_s v}{A} - 1\right)^2 + 20\left(\frac{K_t K_s v}{A} - 1\right)^6 \qquad \frac{K_t K_s v}{A} > 1,\ F_D(v) \le 100\% \quad (3)$$

where v is the standard gust speed, K_t is the terrain multiplier, K_s is the shielding multiplier, A = 30 for pre-1980 construction and A = 37.5 for post-1980 construction. The model was developed from insurance loss data and expert judgment, and includes building and contents damage. Houses built in North Queensland after 1980 represent enhanced wind resistant standards as a result of the devastating damage caused by Cyclones Althea and Tracy in 1971 and 1974, respectively. The damage is expressed as a percentage of insured value. Figure 1 shows the vulnerability model for residential construction. See Stewart (2003) for a full description of the building vulnerability model.

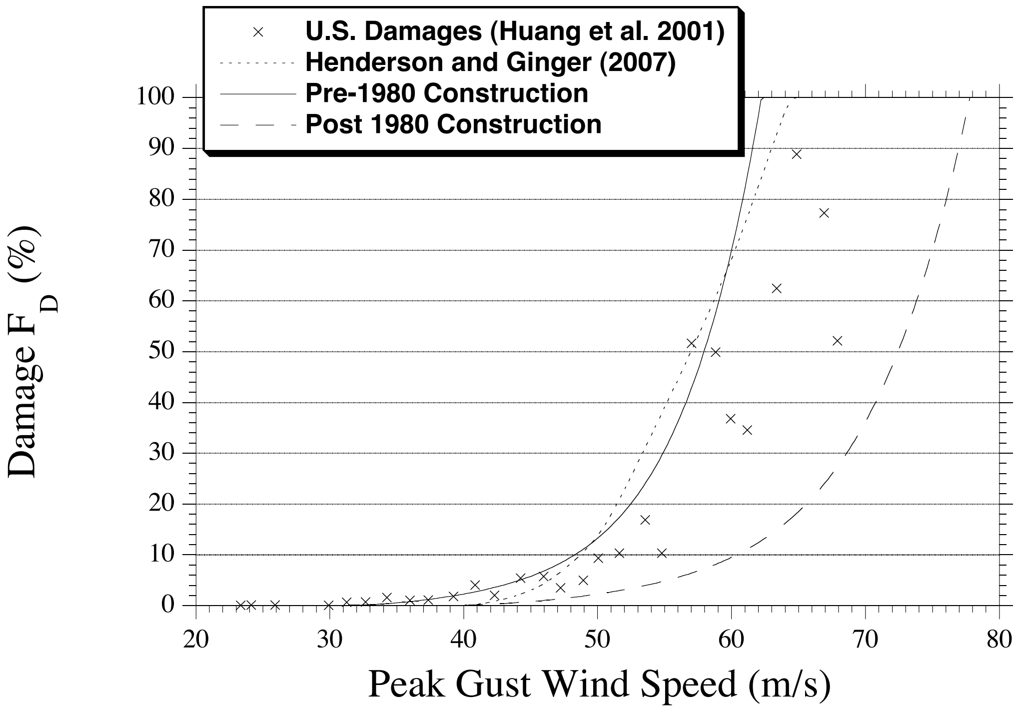

Figure 1. Damage Vulnerability Functions for Residential Construction.

Henderson and Ginger (2007) developed a probabilistic model of component and connection strengths for high-set houses typically built in the 1960's and 1970's in Townsville, Darwin and other locations in Northern Australia. Their building vulnerability model for this type of pre-1980 construction is also shown in Figure 1 where it is seen to be in good agreement with Eqn. (3) for pre-1980 construction. The Henderson and Ginger (2007) building vulnerability model also compared very well with damage data from Cyclones Althea and Tracy. Figure 1 also shows that hurricane damage in the U.S. from Hurricanes Andrew and Hugo (1989, 1992) is bounded by the vulnerability of pre-1980 and post-1980 constructions. These comparisons provide some evidence that the vulnerability models proposed by Walker (1994) are in the ‘right ballpark’. It also suggests that housing that existed in the Southeastern U.S. during the period 1989–1992, particularly its vulnerability to minor damage, is generally representative of Australian pre-1980 construction quality. This is consistent with general observations made by Reardon and Meecham (1993).

It is clearly acknowledged by Walker (1994) that this building vulnerability model is subject to considerable uncertainty. However, it is a very useful starting point for quantifying the effectiveness of strengthened building standards (or enforcement). The general belief, from experimental testing, damage surveys and anecdotal evidence, is that many strengthening procedures, if properly designed and installed, will significantly reduce vulnerability. The building vulnerability model shown in Figure 1 clearly supports this belief.

House locations are defined by the following three exposure categories (Stewart 2003): Foreshore (1 km from coast), Town (1-2 km from coast), Inland (>2 km from coast). The terrain and shielding multipliers for the three exposure categories are listed in Table 1. Since the risk assessment is to be conducted on a regional scale local topographic features were not considered.

Site exposure	Terrain multiplier, K_t	Shielding multiplier, K_s
Foreshore	0.946	1.0
Town	0.864	0.85
Inland	0.864	1.0

Table 1. Terrain and Shielding Multipliers.

4. ANNUAL AND CUMULATIVE DAMAGES

The annual insured damage risk in terms of percentage damage D(t) in year t caused by a wind hazard can be calculated by

$$D(t) = \int F_D(v) f_v(v) dv \tag{4}$$

where $F_D(v)$ is the vulnerability function defined in Eqn. (3) and $f_v(v,t)$ is the time-dependent probability density function for cyclone wind speed given by Eqn. (2). Of more interest to decision-makers may be annual or cumulative monetary damages or losses. The expected annual damage loss expressed in dollars is

$$L_c(t) = \sum_{j=1}^{N} \frac{\alpha_{Ej}\left[D_{pre}(t)N_{pre}(t) + D_{post}(t)N_{post}(t)\right]C_I}{(1+r)^t} \tag{5}$$

and so the expected cumulative damage costs starting at time t_o and extending over a time period T is

$$L_c(t_o,T) = \sum_{t=t_o}^{T} L_c(t) \tag{6}$$

where $D_{pre}(t)$ and $D_{post}(t)$ are the damage risk associated with pre-1980 and post-1980 construction, $N_{pre}(t)$ and $N_{post}(t)$ are the numbers of houses constructed to pre-1980 and post-1980 standards in a region in year t, N is the number of exposure locations, α_{Ej} represents the distribution of houses in each exposure site, taken as 0.2, 0.6 and 0.2 for foreshore, town, and inland, respectively (Stewart 2003), r is the discount rate, and C_I is the insured value of a house. For all scenarios considered herein it is assumed that the wind speed characteristics are constant across a region.

Note also that the damage risks and losses calculated herein are based on a region wide analysis of wind speeds and housing demographics. A more detailed (GIS-based) probabilistic wind field model that considered local topographical factors would produce a wider range of damage risks; namely, some localities within a region would have higher damage risks and others lower even though they may both be located in the same broad exposure category used herein. Hence, although the economic risks to be calculated herein will be subject to considerable uncertainty they are well suited for comparative analyses such as that conducted herein.

According to Australian 2001 census data there are approximately 125,000 dwellings (houses, units, apartments) in coastal regions of North Queensland, most of these are located in the large coastal cities of Cairns and Townsville (ABS 2001), 50% of which are pre-1980 houses and the rest are assumed to be built according to post-1980 building standards (Stewart 2003). In the period 2008 to 2025 it is estimated that 50,000 new dwellings will be required to accommodate projected population growth (QG 2008). Over a 50 year period 2001 to 2050 this is equivalent to a growth of roughly 100%. By 2050, the total house numbers will thus increase by 100% to 250,000, i.e. 2,500 new dwellings built each year for the next 50 years. For regional damage estimates, the proportion of Foreshore-Town-Inland construction is assumed constant at 20%-60%-20% over the 50 year time frame. This scenario is based on several assumptions, but more accurate demographic and housing studies can be used to refine the scenario assumed herein.

The median replacement value of a house in North Queensland is approximately \$215,000 (Li and Stewart 2008). The insured value of the house is higher than the replacement value due to many homeowners also holding contents insurance, which led Huang et al. (2001) to assume that the insured value of a house is 150% of the (replacement) value of the structure. It follows that the median insured value of a house in North Queensland is approximately C_I=\$320,000 in 2008 terms.

Figure 2 shows the annual damage (percentage of insured value) risks D(t) obtained from Eqn. (4) for houses built with pre-1980 and post-1980 standards in a foreshore location, assuming 0%, 10% or 25% increase in wind speeds. As expected, the annual damage risks for pre-1980 and post-1980 construction increase with time if wind speed increases with time. The annual damage risks for pre-1980 construction are approximately 4-7 times higher than post-1980 construction risks.

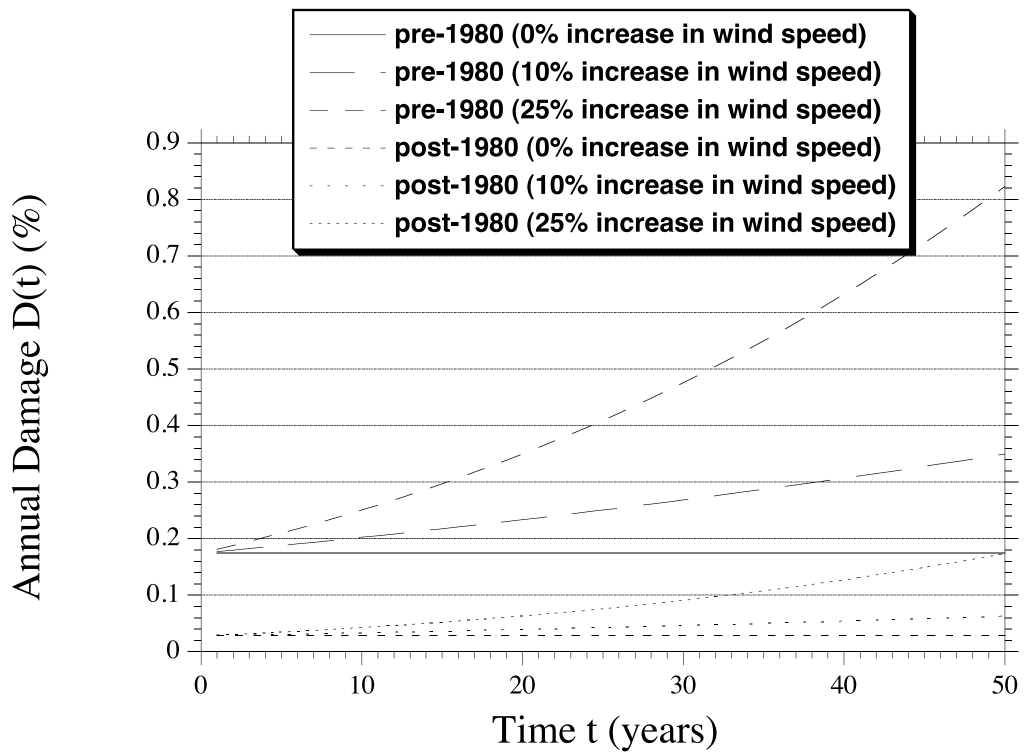

Figure 2. Annual Damage Risk D(t) for Pre-1980 and Post-1980 Construction in Foreshore Exposure, with 0%, 10% and 25% Increase in Wind Speed.

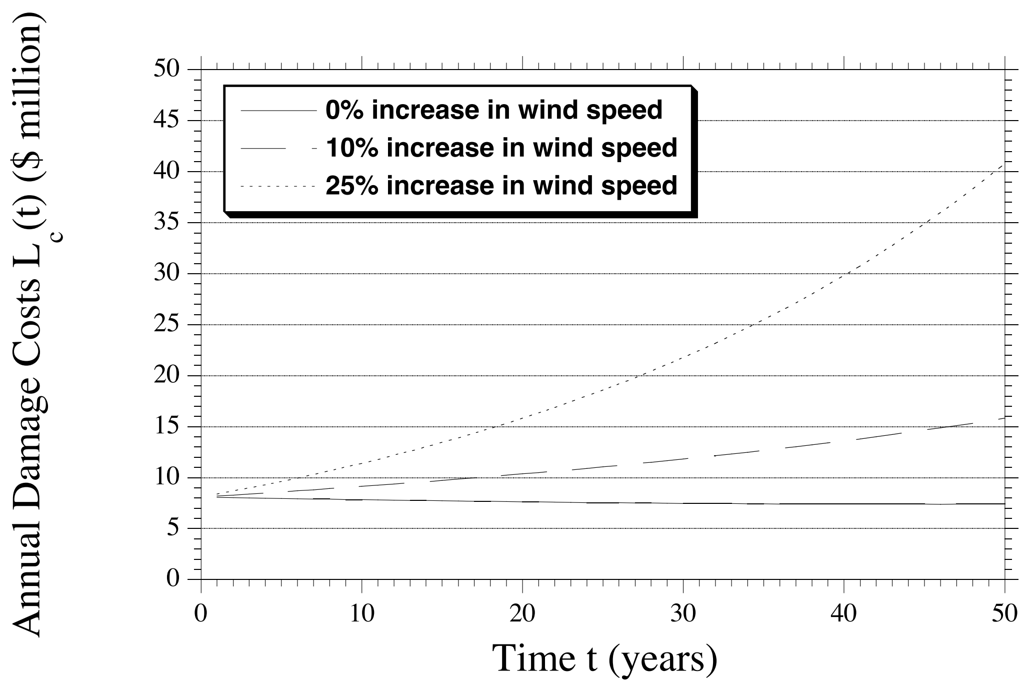

Figure 3. Annual Damage Costs for Foreshore Region.

If it is assumed that in 50 years time the number of pre-1980 houses will gradually decrease by 50% to 31,250 houses, either due to the replacement of old houses or renovations or retrofit of pre-1980 houses to meet enhanced building standards. Hence, in 50 years time $N_{pre}(50)$=31,250 houses and $N_{post}(50)$=218,750 houses. The annual damage costs for the foreshore region are calculated from Eqn. (5) for N=1 and α_{Ej}=0.2 and are presented in Figure 3, assuming no discounting (r=0%). The annual damage costs with no climate change decreases with time because of the growth in new housing numbers (with reduced vulnerability). However, for a 10% increase in wind speed the annual regional damage risks double over the 50-year period. A 25% increase in wind speed will increase regional damage considerably with annual damage costs of up to $41 million compared to $7 million for a 0% increase in wind speed.

Figure 4 shows the cumulative regional damage costs $L_c(0,50)$ for pre-1980 and post-1980 construction in the three exposure categories, with the scenarios of increases in wind speed from 0-25% and no discounting is assumed. It can be seen that the most severe losses in 50 years will occur to pre-1980 construction in foreshore locations. If a 25% wind speed increase in expected then damage to pre-1980 construction in foreshore locations reaches $600 million over 50 years. Clearly, the majority of wind damage occurs to the pre-1980 construction for all exposure locations in North Queensland.

Figure 5 shows the regional cumulative damage costs $L_c(1,T)$ for North Queensland, over intervals of T=10, 25 and 50 years, N=3 and assuming no discounting (r=0%). It is observed that the cumulative damage costs in 50 years is $690 million if there is no climate change, and the losses increase to $1.073 and $2.017 billion when the cyclone intensity is assumed to increase by 10% and 25% in 50 years time, respectively. These are a 56% and 192% increase in total losses for the region over 50 years assuming 10% and 25% wind speed increase when compared to the no climate change scenario. However, increases in damage costs are only 9% and 25% (for 10% and 25% increases in wind speed) if a more immediate time period is considered (next 10 years). This demonstrates that damage costs will accelerate over time, and the longer the time period considered the greater the proportional increase in damage costs when compared to the no climate change scenario. For more details about cyclone damage risks see Li and Stewart (2008).

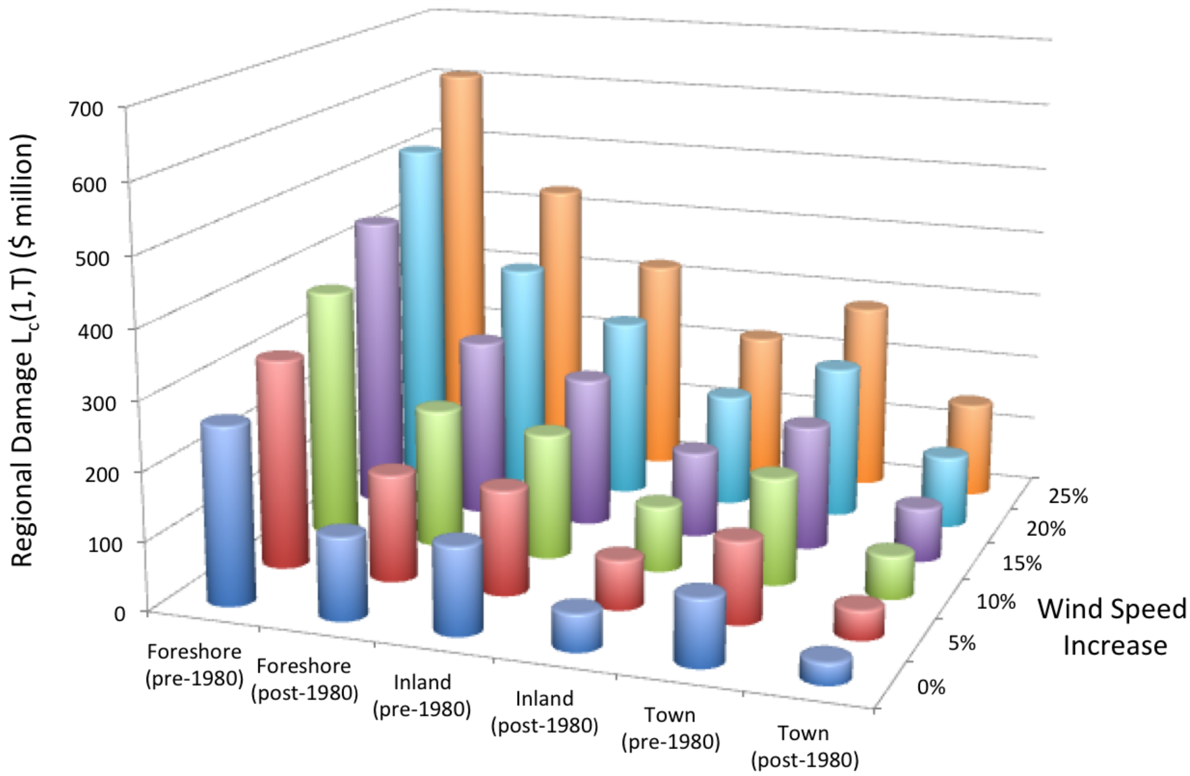

Figure 4. Cumulative Regional Damage Costs in 50 years for Pre-1980 and Post-1980 Construction in Foreshore, Inland and Town Exposures.

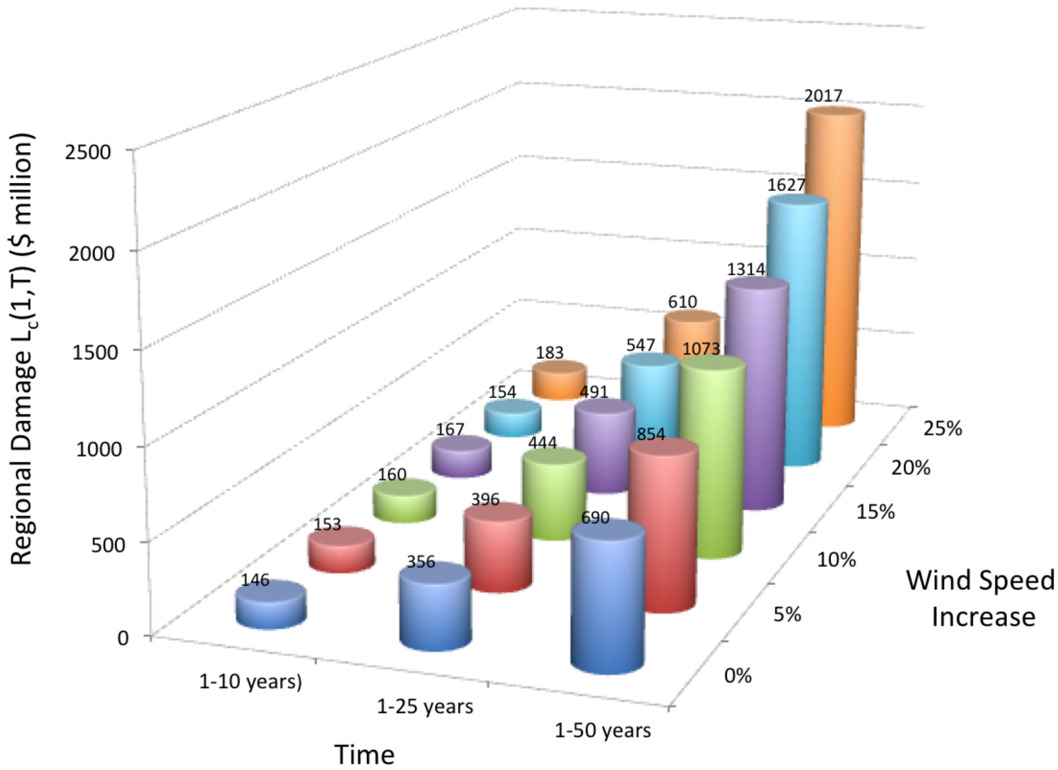

Figure 5. Regional Cumulative Damage Costs in North Queensland.

As there is significant uncertainty about climate change scenarios and their timeframe, a 'fragility' type curve may be useful that shows the increase in regional damages for various wind speed increases taken over several time periods, in this case 2030, 2050, 2070 or 2100 where time is measured from 2010 - see Figure 6. Figure 6 shows that the increase in regional damage costs may exceed several billion dollars for some extreme (worst case) climate change scenarios, but may be as low as a few hundred million dollars if the climate change scenario predicts a small increase in wind speed.

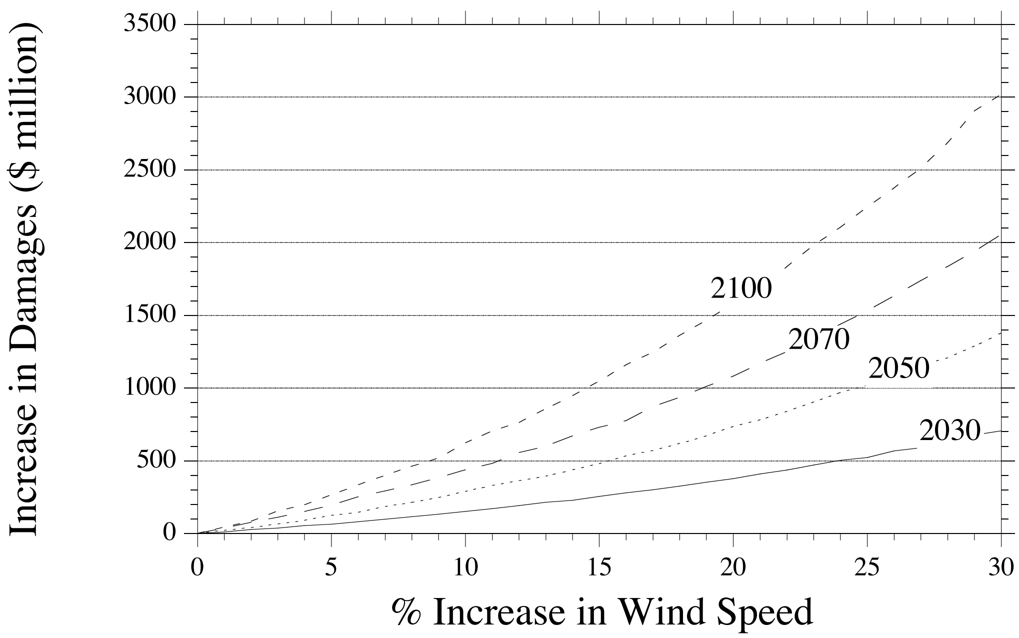

Figure 6. Regional Increases in Damage Costs for Various Climate Change Scenarios and Time Periods.

5. COST-EFFECTIVENESS OF CLIMATE ADAPTATION STRATEGIES

The situation assuming no climate adaptation strategies is referred to herein as the 'do nothing' scenario. While recognising that future changes to housing demographics is imprecise, a reasonable assumption may be that over the next 50 years there will be no retrofit to pre-1980 construction, that the housing mix is 50-50 (pre-1980 to post-1980) at year 1 and the rate of new (post-1980) construction is 2,500 houses per year. Thus, the “do nothing" regional loss estimation is

$$L_c(t_o,T) = \sum_{t=t_o}^{T}\sum_{j=1}^{N}\frac{\alpha_{Ej}\left\{62{,}500D_{pre}(t) + 62{,}500D_{post}(t) + 2{,}500tD_{post}(t)\right\}C_I}{(1+r)^t} \tag{7}$$

where $N_{pre}(t)=N_{post}(t)=62{,}500$ houses.

The cost-effectiveness of various retrofit strategies to adapt to climate change is investigated by comparing regional loss for the following climate adaptation strategies:

1. retrofit/strengthen pre-1980 construction at selected high wind exposure sites (foreshore exposure) to enhanced (post-1980) standards,
2. retrofit/strengthen pre-1980 construction in the whole region to enhanced (post-1980) standards, or
3. reduce vulnerability of new construction at selected high wind exposure sites (foreshore exposure).

The regional loss for climate adaptation strategies 1 and 2 are

$$L_{c-adapt}(t_o,T) = \sum_{t=t_o}^{T}\sum_{j=1}^{N}\frac{\alpha_{Ej}\left\{62{,}500\left[\left(\frac{100-nt}{100}\right)D_{pre}(t) + \frac{nt}{100}D_{post}(t) + \frac{n}{100}\left(\frac{C_{st}}{1.5}\right)\right] + 62{,}500D_{post}(t) + 2{,}500tD_{post}(t)\right\}C_I}{(1+r)^t} \quad nt \le 100$$

$$L_{c-adapt}(t_o,T) = \sum_{t=t_o}^{T}\sum_{j=1}^{N}\frac{\alpha_{Ej}\left\{125{,}000D_{post}(t) + 2{,}500tD_{post}(t)\right\}C_I}{(1+r)^t} \quad nt > 100 \tag{8}$$

where C_{st} is the cost of retrofit expressed as percentage of house replacement value and n is the percentage rate of retrofitting. Note that if n=10% then all pre-1980 construction will be retrofitted in 10 years, but if n=1% then only 50% of pre-1980 construction will be retrofitted in 50 years.

The regional loss for climate adaptation strategy 3 where each year all of the 2,500 new houses are strengthened to reduce vulnerability by R% is

$$L_{c-adapt}(t_o,T) = \sum_{t=t_o}^{T}\sum_{j=1}^{N}\frac{\alpha_{Ej}\left\{62{,}500D_{pre}(t) + 62{,}500D_{post}(t) + 2{,}500t\left(\frac{100-R}{100}\right)D_{post}(t) + 2{,}500\left(\frac{C_{st}}{1.5}\right)\right\}C_I}{(1+r)^t} \tag{9}$$

The cost of retrofitting (C_{st}) is very much dependent on the required reduction in vulnerability, structural configuration, and current design and construction practices. So it is difficult to estimate costs accurately. Nonetheless, AGO (2007) estimated that the increase in construction cost of new houses due to an increase in design wind class (say C1 to C2) is approximately \$2,000 to \$6,000 per house. If the median replacement value of a house in North Queensland is \$215,000 then these increases in C_{st} are 1-3% of the value of the house. A number of other studies have found that the additional cost to new housing for increased cyclone resistance is in the range of 1–10% (e.g. Stewart et al. 2003) and approximately 5% for Australian cyclone resistant systems (Reardon and Oliver 1983). There is very little data on the costs of retrofitting an existing house for increased cyclone resistance. However, Leicester (1981) has observed that 'estimated' additional costs for houses in Australia range from 15% to 50% for retrofit of existing houses. There can be expected to be a relatively wide range of retrofit costs (C_{st}) due to the large choice of strengthening procedures available for housing construction.

The analysis assumes that the cost of retrofit will be an additional cost, borne by the residential home owner, government or other agency. For example, if a climate adaptation measure is likely to reduce damages in a cost-effective manner then government may invest resources into funding the costs of a climate change adaption programme. Alternatively, insurers may provide a reduction in premiums for homeowners that retrofit their houses. Either way, these are pro-active measures that, for appropriate climate adaptation programs, will benefit home owners, insurers, society (less social disruption) and government.

The effects of three climate adaptation strategies are now discussed assuming a 10% increase in wind speeds over the next 50 years and a discount rate of r=4%. Note that the net benefit of an adaptation strategy is $L_c(t_o,T)-L_{c\text{-}adapt}(t_o,T)$ and the percentage change in net benefit is $100(L_c(t_o,T)-L_{c\text{-}adapt}(t_o,T))/L_c(t_o,T)$. The percentage change in net benefit is not affected by the number of houses in the region as this will influence $L_c(t_o,T)$ and $L_{c\text{-}adapt}(t_o,T)$ equally. For example, if the number of houses in the region is reduced by 50% then $N_{pre}(1)=N_{post}(1)=31,250$ houses and new houses increase by only 1,250 houses/year then $L_c(t_o,T)$ and $L_{c\text{-}adapt}(t_o,T)$ reduce by 50%, but percentage change in net benefit is unchanged.

5.1 Adaptation Strategy 1: Effect of retrofitting foreshore construction

Figure 4 shows that the annual damage for foreshore construction is many times the damage for inland and town exposures. Thus, an effective adaptation strategy is likely to be one that focuses on reducing vulnerability in foreshore locations rather than all houses in the North Queensland coastal region. The regional loss for retrofitting pre-1980 construction in foreshore locations is estimated from Eqn. (8) where N=1 and α_{Ej}=0.2. The net benefit over 50 years for a wind speed increase by 10% by year 50 with n=1-10% and C_{st}= 2.5-25% is shown in Figure 7. For example, if the retrofit of all pre-1980 construction is completed in 10 years (n=10%), the net benefit is \$86.5 million if the retrofit cost is C_{st}=2.5%. The adaptation strategy is also cost-effective if C_{st}=5% but the net benefit reduces to as little as \$4.7 million. If C_{st} is 10% or higher then adaptation strategy 1 is not cost-effective. As the retrofitting process accelerates (n increases), the cost-effectiveness is more prominent. Figures 8 and 9 show when an adaptation strategy becomes economical viable (i.e. the net benefit is positive). When retrofit cost is C_{st}=1% it takes only eight years for the adaptation strategy to be cost effective regardless of the annual upgrading rate (n). However, as C_{st} increases it takes a longer time for the adaptation strategy to become economically viable.

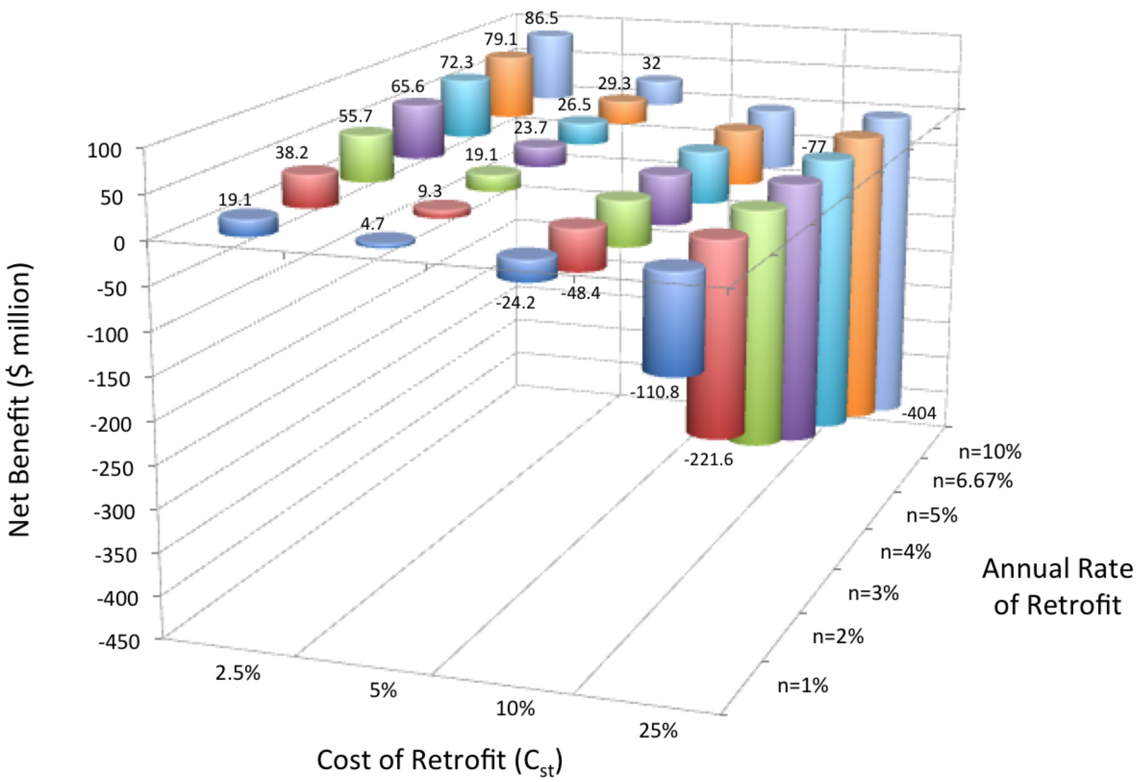

Figure 7. Net benefit for Adaptation Strategy 1 (retrofit foreshore construction).

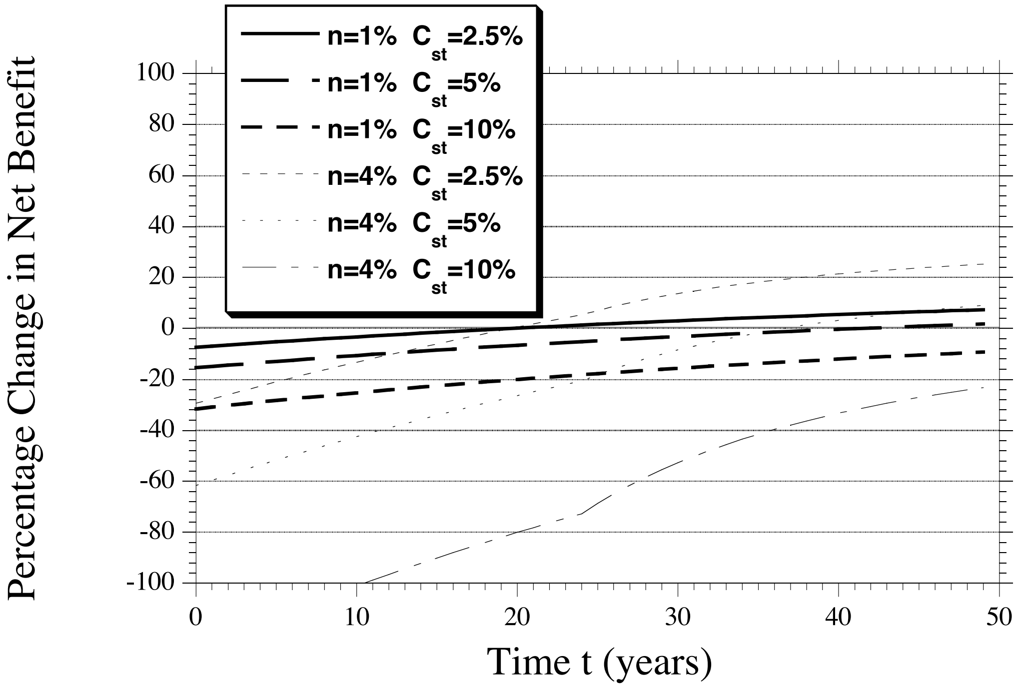

Figure 8. Percentage Increase in Net Benefit for Adaptation Strategy 1.

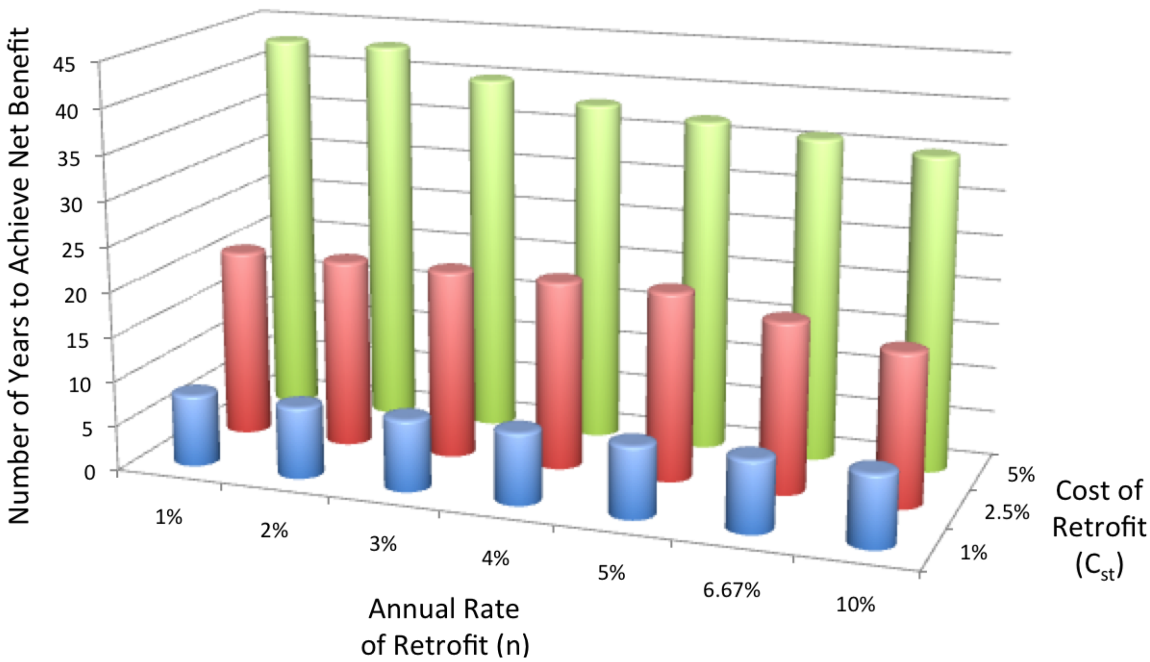

Figure 9. Time Needed for Adaptation Strategy 1 to be Cost-effective.

Table 2 shows that adaptation strategy 1 is cost effective as long as C_{st} is less than 5.81-6.49% of house value (approximately $12,000 to $14,000). This appears to be a relatively small cost, however, as discussed above, the cost of retrofitting an existing house is likely to be much higher (say C_{st}=15-50%) which would suggest that ensuring that adaptation strategy 1 is cost-effective may be difficult to achieve in practice. However, retrofit costs are highly variable, and so it is not possible for the present paper to assess if retrofitting sufficient to enhance a pre-1980 house to post-1980 standards can be undertaken for C_{st} less than 5-6%.

	n=1%	n=2%	n=3%	n=4%	n=5%	n=6.67%	n=10%
Maximum Retrofit Cost C_{st} (%)	5.81	5.83	6.31	6.41	6.45	6.47	6.49

Table 2. Maximum Retrofit Cost C_{st} for Adaptation Strategy 1 to be Cost-effective.

The 'do nothing' scenario assumed herein is believed the most realistic, but there are other possibilities for time-dependent changes in construction over the next 50 years. One scenario might be that some pre-1980 construction will be retrofitted over the next 50 years due to home renovations, demolition and other owner initiated improvements. In this case, it may be that (say) 50% of pre-1980 construction will be upgraded over 50 years (i.e. n=1%) at no cost to government. The net benefit for this case is reduced from that discussed above, so that retrofit costs of C_{st}=5% are no longer cost-effective. A retrofit cost of only C_{st}=2.5% is cost-effective for this alternate 'do nothing' scenario. Finally, if the discount rate is taken as less than 4% then net benefit will increase as this will increase the present value of future losses which will make adaptation strategies more cost-effective.

5.2 Adaptation Strategy 2: Effect of retrofitting all pre-1980 construction to post 1980 standards

The regional loss for adaptation strategy 2 are calculated from Equation (8) where N=3 using data from Table 1. It can be observed from Figure 10 that this retrofit strategy is marginally cost-effective only if C_{st} is 2.5% or less and the annual upgrading rate (n) is 4% or higher. Clearly, when compared to adaptation strategy 1 (see Figure 7), retrofitting all pre-1980 construction is significantly less cost-effective than retrofitting houses only in vulnerable exposures such as foreshore locations.

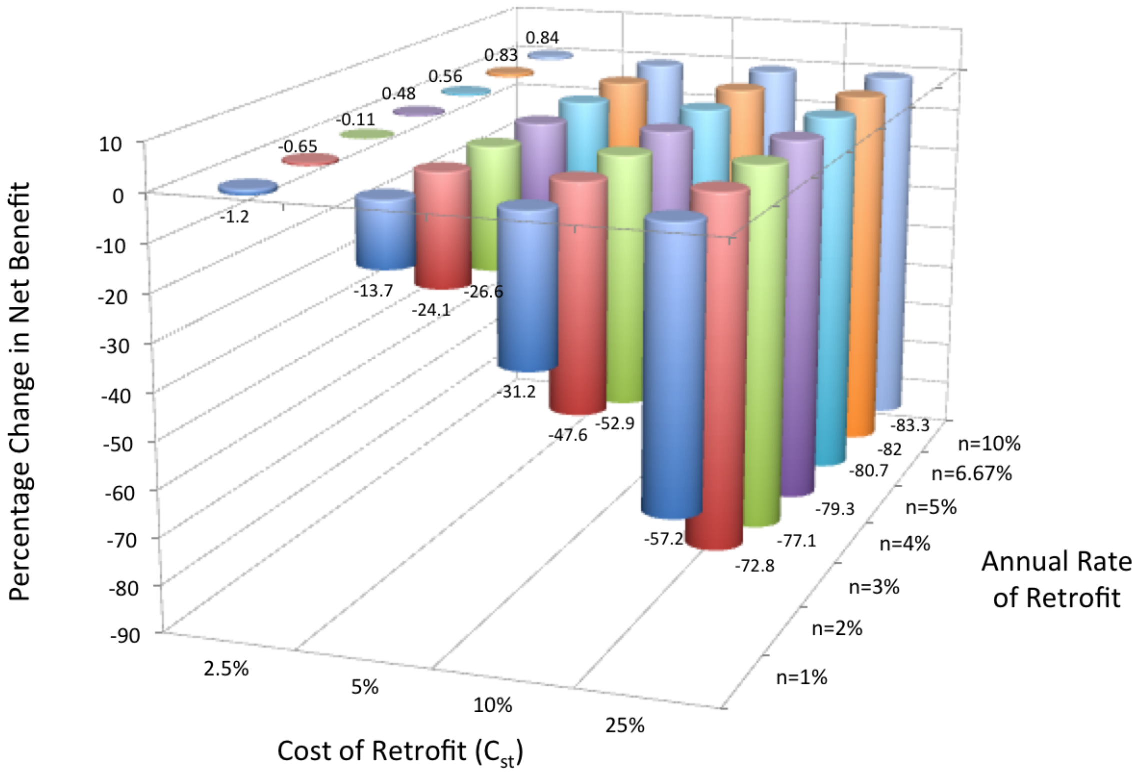

Figure 10. Cost-effectiveness of Adaptation Strategy 2.

5.3 Adaptation Strategy 3: Effect of improving new foreshore construction

Figure 11 shows the percentage change in net benefit calculated from Eqn. (9) when vulnerability of new construction is reduced by R=50%. Note that the reduction in vulnerability applies only to new construction in foreshore locations (N=1). A reduction in vulnerability of 50% is significant, but Figure 11 shows that this adaptation strategy is not cost-effectiveness even if C_{st} is as low as 1%. Adaptation strategy 3 is only cost-effectiveness if C_{st} is less than 0.55% (approximately $1,200). Given that the additional cost to new housing for increased cyclone resistance is in the range of 1–10% it may be difficult to achieve a 50% reduction in existing vulnerabilities for an additional cost of no more than 0.55% of the value of the house.

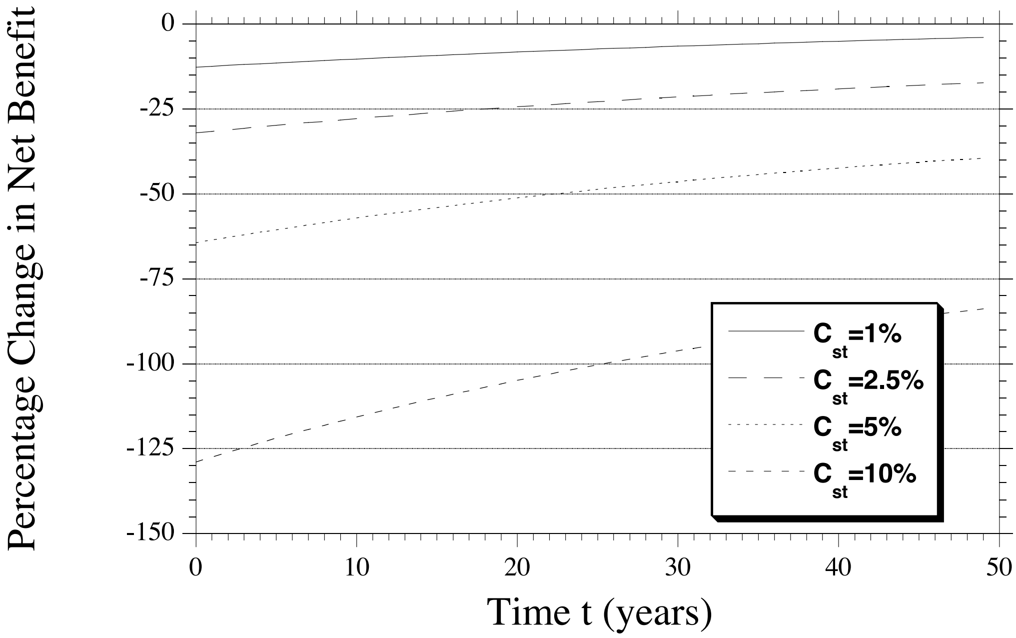

Figure 11. Percentage Increase in Net Benefit for Adaptation Strategy 3 (new construction).

5.4 Other Climate Change Scenarios

There is significant uncertainty about future predictions in wind speeds due to enhanced greenhouse conditions. Hence, percentage increases in net benefit are calculated for 50-year wind speed increases of 5% and 25% which are shown in Figures 12 and 13 for adaptation strategy 1. A retrofit cost of C_{st} =10% now becomes cost-effective for a 25% increase in wind speed, but is not cost effective for wind speed increases of 5% or 10%. As expected, the benefit of adaptation strategies increases as the cyclone intensity increases with time.

If the wind speed increase is 25% then the percentage increase in net benefit for adaptation strategy 2 (retrofit all pre-1980 construction) varies from 6.2% to 27% for C_{st}=2.5% depending on the annual upgrading rate (n=1-10%). On the other hand, it is not cost-effective to adopt adaptation strategy 2 if there is only a 5% increase in wind speed over the next 50 years. Adaptation strategy 3 (i.e. strengthen new construction) will only be cost-effective when C_{st}=1.75% and if the wind speed is assumed to increase by 25% over 50 years.

To be sure, the results presented herein are sensitive to the selected or assumed parameter values. Nevertheless, the results provide a reasonable indication of the relative measures of cost-effectiveness for some typical climate adaptation strategies. If more detailed information becomes available then the risk-based decision support framework developed herein can be applied to such cases to provide improved decision support.

6. FURTHER WORK

There is clearly much scope for further work. This may include developing building vulnerability models for different housing types or construction techniques (and materials), age profiles, code specifications, compliance and enforcement, changes in exposure categories (e.g., effect of increased urbanisation), and so on. The development of such models will require a substantial research effort that may include: field or test data of building performance; component and structural system strength prediction modelling; assessing the effect of component and structural system strength on the integrity of the building envelope; and probabilistic structural response modelling to develop vulnerability (fragility) curves. The work by Henderson and Ginger (2007) provides a framework for such modelling. There is also a need to relate failure of a component, structural system or building envelope to economic losses needed for vulnerability models. Such economic data may be obtained from the collection and analysis of insurance loss data or from expert judgements.

A risk analysis for a specific region will require an accurate and detailed probabilistic wind field model capable of considering topographic, terrain roughness and shielding effects. The demographics of housing into age, style, etc. will also be required, and will be influenced by the resolution of the probabilistic wind field model. Finally, more rigorous economic decision analyses may be developed that consider the effect of insurance premiums, excess, insurer incentives, discount rates, exposure periods, life safety, cyclone mitigation and response costs and other costs and benefits of cyclone adaptation strategies related to the building owner, insurer, reinsurance company, government agency or society in general. This will require a more detailed multi-attribute decision support analysis.

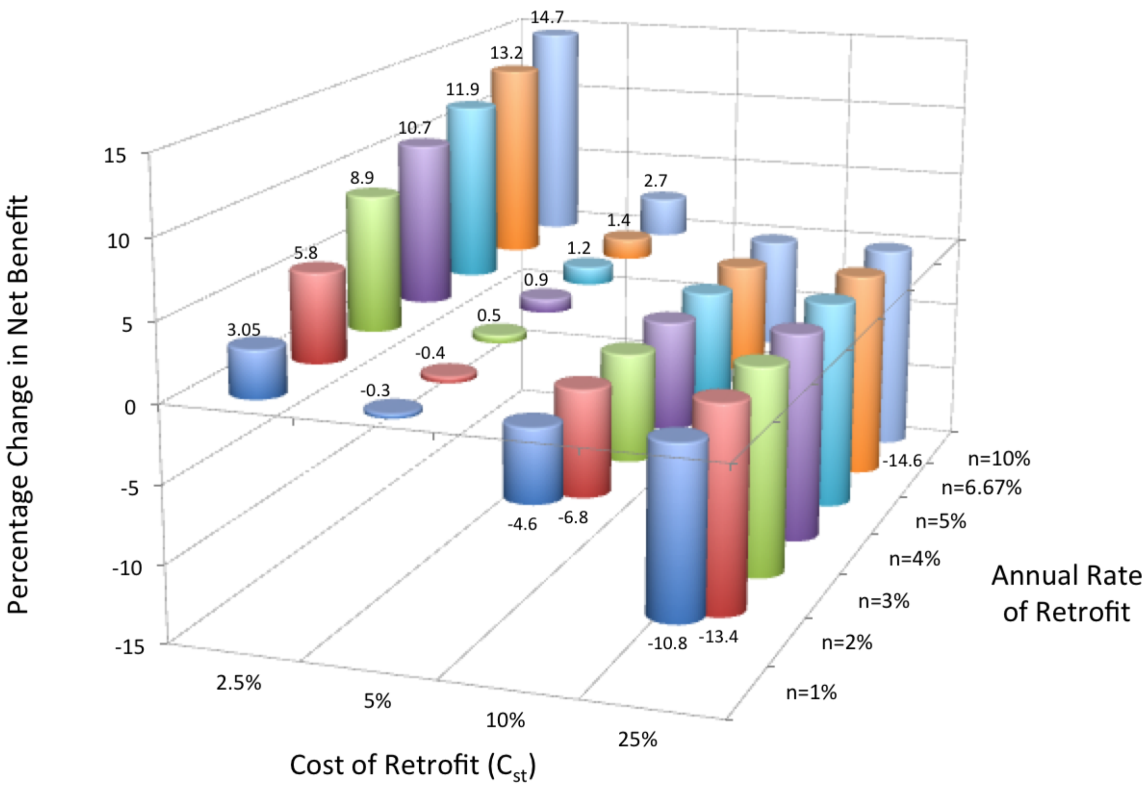

Figure 12. Cost-effectiveness of Adaptation Strategy 1, for 5% Increase in Wind Speed.

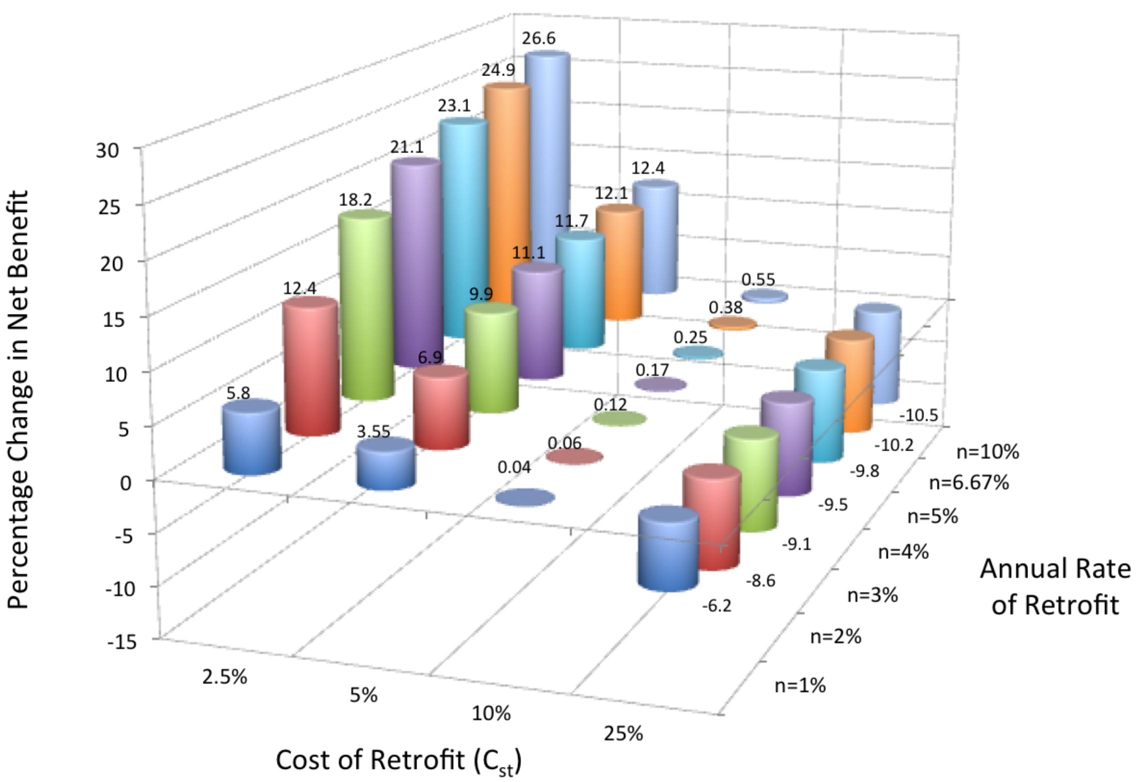

Figure 13. Cost-effectiveness of Adaptation Strategy 1, for 25% Increase in Wind Speed.

7. CONCLUSIONS

Cyclone damage risks to residential construction as a result of climate change and examining the cost-effectiveness of different adaptation strategies are estimated from a risk-cost-benefit analysis. Adaptation strategies considered include (i) retrofitting older (pre-1980) construction in the North Queensland region to enhanced standards, (ii) retrofitting only the older construction at selected high wind exposure sites or (iii) reducing the vulnerability of new construction. The worst-case scenario of a 25% increase in cyclone intensity in 50 years will result in over $1 billion of damages - nearly triple the expected total insured damage for North Queensland assuming no climate change. In comparison, an increase in wind speed of 5% or 10% will increase damage costs for the same region by 24% or 56%, respectively. It was found that it is cost-effective for older residential construction located in foreshore (high vulnerability) locations in North Queensland to be retrofitted to higher wind resistant standards if such retrofitting costs less than approximately 6% of the house replacement value, when wind speed is expected to increase by 10% in 50 years. If wind speed is expected to increase by 25%, it is cost effective to (i) retrofit all pre-1980 construction at all sites with retrofit cost less than 2.5% of house value or to (ii) retrofit houses in foreshore locations if such retrofitting costs less than approximately 10% of house value.

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