

Risk assessment and economic viability of climate adaptation measures for Australian housing subject to extreme wind events

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Abstract: Australia is a continent subject to climatic extremes, and its losses from tropical cyclones and thunderstorms are significantly higher than other natural hazards. The number of severe tropical cyclones is likely to increase due to climate change. Brisbane and the northeast coast of Queensland are regions where design wind specifications may be inadequate under future climate conditions. For example, the Australia Building Codes Board is considering a shift in the boundary to cyclone Region C to extend it south on the Queensland coast to 27°S to include areas in the Sunshine Coast. Hence, there is an urgent need to assess the risks and economic viability of these climate adaptation measures.

An appropriate adaptation strategy may be one that increases design wind speeds for new houses leading to reduced vulnerability of new construction. The present paper will assess the damage risks, adaptation costs and cost-effectiveness of this adaptation measure for residential construction in the Queensland cities of Cairns, Townsville, Rockhampton and Brisbane assuming time-dependent changes in frequency and intensity of cyclonic and non-cyclonic winds to 2100. Advanced spatial and temporal stochastic simulation methods will be used to include uncertainty and variability of climate and building vulnerability on damage risks. The criteria for cost-effectiveness are reduction in present value measured by Net Present Value (NPV) and probability that NPV exceeds zero. The simulation analysis found that increasing the wind classification for design of new housing (at a cost of \$3,700 per house) for all cities can produce a mean NPV that exceeds \$8.3 billion by 2100 assuming a 4% discount rate (see Figure 1). The benefits are highest for Brisbane due to its high exposure (large population) and relatively high vulnerability of existing residential construction. Retrofitting older houses is a more costly adaptation strategy which mostly resulted in a net loss. We also showed that the benefits of adaptation strategies are maximised if they are implemented promptly, but deferral to 2020 or 2030 will still result in a net benefit.

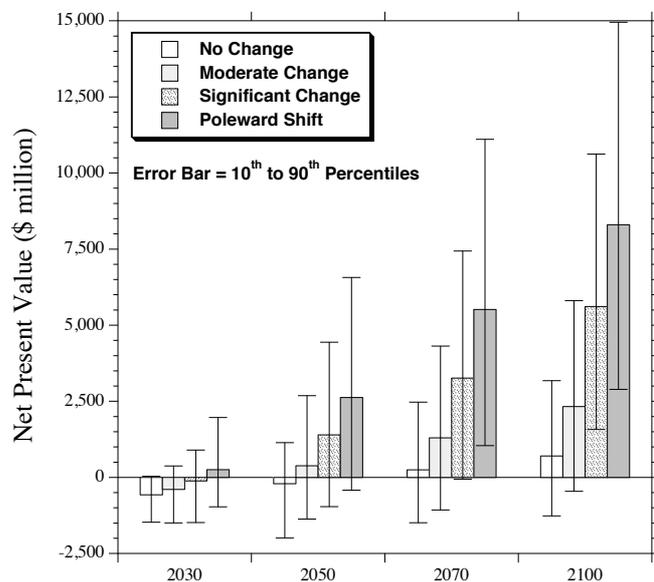


Figure 1. Mean and 10th and 90th percentile Net Present Values for increases in wind classifications for new houses that reduces vulnerability of new construction.

Keywords: Risk, Cost-Benefit Analysis, Climate Adaptation, Climate Change, Infrastructure

1. INTRODUCTION

Climate change researchers suggest that significant alteration in severe wind intensity and frequency are possible within the lifetime of existing infrastructure in Australia. Most cyclone risk research assumes a stationary climate. However, recent preliminary work by Li and Stewart (2011) and Bjarnadottir et al. (2011) have assessed the risks and cost-effectiveness of adaptation strategies for houses in North Queensland and Florida subject to cyclones for varying climate scenarios. This paper considers both cyclonic and non-cyclonic wind fields, and improved wind vulnerability models with more comprehensive wind exposure and housing growth data to identify cost-effective adaptations involving considerable uncertainties.

The current Australian Standard “Wind Loads for Houses” AS4055-2006 is the reference standard used to determine the appropriate wind classification for design of residential (domestic) housing. These wind classifications are then used to determine appropriate deemed-to-comply sizing and detailing requirements for residential construction. However, the wind classifications may be inadequate if wind speeds increase due to a changing climate. The vulnerability of new residential construction may be reduced by increasing design wind speeds to resist 50% higher wind pressures. The economic viability of such an adaptation option at a regional scale is affected by both spatiality in construction distribution and temporal uncertainty in extreme wind development. The present paper will assess the damage risks, adaptation costs and cost-effectiveness of these adaptation measures for residential construction in Queensland cities to 2100. The stochastic analysis includes the effect of climate change on time-dependent wind field characteristics, costs of adaptation, timing of adaptation, discount rates, future growth in new housing, and fragility of houses to wind speed. This will provide practical advice to policy makers to help ‘future proof’ built infrastructure to a changing climate.

Results are presented for various climate change scenarios to 2100 for four cities: Cairns, Townsville, Rockhampton and Brisbane, along Queensland’s east coast where cyclones and storms are the dominant natural hazard. The criterion for cost-effectiveness is net present value NPV (or net benefit equal to benefits minus the cost). However, the stochastic analysis also calculates the probability that an adaptation measure will have NPV>0, indicating the confidence level of adaptation effectiveness. We considered four climate scenarios: no change, moderate change (25% reduction in cyclone frequency, 10% increase in wind speeds), significant change (20% increase in wind speeds), and poleward shift in cyclones to Brisbane by 2100. More details of the analysis and results are described by Stewart and Wang (2011).

2. CLIMATE CHANGE PROJECTIONS OF WIND SPEEDS

The East coast of Queensland is a cyclone affected region, but non-cyclonic gust speeds tend to dominate in South-east Queensland. The cumulative distribution function for annual maximum gust speed is:

$$F_v(V, t) = \left\{ 1 - \lambda(1 + \gamma_F(t)) \left[1 - k_p \left(\frac{v/(1 + \gamma_{cyc}(t)) - u_p}{\sigma_p} \right)^{1/k_p} \right] \right\} \left\{ 1 - \exp \left(- \frac{v_e - v/(1 + \gamma_{mean}(t))}{\sigma_e} \right) \right\} \quad (1)$$

where v is the 3-second gust wind speed, λ is the frequency of cyclonic winds, $\gamma_F(t)$ is the time-dependent change to frequency λ , $\gamma_{cyc}(t)$ is the increase in mean cyclonic wind speed with time, σ_p is the scale parameter, k_p is the shape parameter, u_p is the threshold value, $\gamma_{mean}(t)$ is the time-dependent increase in non-cyclonic gust wind speed, and v_e and σ_e are the location and scale parameters for non-cyclonic winds. Parameter values to describe historical wind events are given by Wang and Wang (2009). Climate change projections will influence $\gamma_F(t)$, $\gamma_{cyc}(t)$ and $\gamma_{mean}(t)$ - see Stewart and Wang (2011)

In Australia, there is a strong tendency for a decrease in cyclone frequency with an average reduction of approximately 50% for the period 2051-2090 in comparison with 1971-2000, but it is also expected that there is increasing likelihood of extreme wind speed from tropical cyclones (Abbs 2010). Studies also indicated that there was low confidence in the projection of the changes in intensity of tropical cyclones in Australia (Knutson 2011). In addition, CSIRO (2007) suggested that the average annual change in mean wind speed is projected to increase up to 19% in Brisbane by 2070 for the A1FI emission scenario. Another possible consequence of climate change is a 2 to 5 degrees of poleward shift of tropical cyclones (CSIRO 2007). Regions historically less subject to cyclones (e.g. Brisbane and Southeast Queensland) may then be more vulnerable to more damaging wind speeds in the future. To allow for a possible poleward shift of up to 4 degrees by 2100, the cyclonic wind field parameters used for Rockhampton are applied to Brisbane. Assuming a gradual poleward shift of tropical cyclones by 2100, then the cyclonic wind parameters λ , σ_p , k_p and u_p will vary with time.

Since there are still many uncertainties to accurately define the future trend of extreme winds in Australia (for review see Stewart and Wang 2011), four wind scenarios are considered:

1. No Change - no change in climate
2. ‘Moderate Change’ - 25% reduction in cyclone frequency, 10% increase in cyclonic and 10% increase in non-cyclonic wind speeds by $t=2100$ ($\gamma_F(t)=-25\%$, $\gamma_{cyc}(t)=10\%$, $\gamma_{mean}(t)=10\%$)
3. ‘Significant Change’ - no change in cyclone frequency, 20% increase in cyclonic and 20% increase in non-cyclonic wind speeds by $t=2100$ ($\gamma_F(t)=0\%$, $\gamma_{cyc}(t)=20\%$, $\gamma_{mean}(t)=20\%$)
4. ‘Poleward Shift’ - 4 degree poleward shift in cyclones to Brisbane by $t=2100$

A time-dependent linear increase of wind speed is assumed (Stewart and Wang 2011). Note that moderate and significant change scenarios increase the 95th percentile non-cyclonic wind speed for Brisbane by 6.0% and 13.3%, respectively.

3. EXPOSURE TO WIND

The Australian Standard “Wind Loads for Houses” AS4055-2006 assesses design wind speeds for housing and so is used herein to determine terrain and shielding effects for houses in an urban environment. The standard AS4055-2006 classifies design loads on new houses into categories N1-N6 and C1-C4 for non-cyclonic and cyclonic regions, respectively. Houses built in North Queensland after 1980 have been built to this enhanced wind resistant standard (and its predecessors) caused by changes to the Queensland Building Act. Houses built prior to 1980 thus have significantly increased vulnerability to wind. The terrain category and associated terrain multipliers for two exposure categories are obtained from AS4055-2006 (see Table 1) and AS4055-2006 assumes full shielding for urban areas.

The number of existing houses in Cairns, Townsville, Rockhampton and Brisbane are 48,000, 56,000, 27,000 and 757,000, respectively. Approximately 5% of houses are located in foreshore

Table 1. Current (AS4055-2006) and Proposed Wind Classifications.

Location	Terrain Category	Terrain Multiplier K_t	Current Wind Classification	Current Design Gust Wind Speed	Proposed Increase in Wind Classification
Cairns, Townsville, Rockhampton:					
Foreshore	TC2	0.99	C2	61 m/s	C3
Non-Foreshore	TC2.5	0.90	C1	50 m/s	C2
Brisbane:					
Foreshore	TC2	0.94	N2	40 m/s	C1
Non-Foreshore	TC3	0.83	N2	40 m/s	C1

locations, and the proportion of 2010 housing stock constructed prior to 1980 is 50% for all locations in Queensland. The time-dependent increase in new housing stock is based on population projections based on Australian Bureau of Statistics (ABS) Series B projections of population growth, and so new housing increases by 2.3% and 2.1% per year for Brisbane and rest of Queensland, respectively. As houses age there is an increasing likelihood that they will experience alterations or additions, and some will be demolished and rebuilt. The ABS also reports that the number of residential buildings undertaking alterations and additions is 15% of new housing numbers. We assume that all alterations will be on those of older pre-1980 construction.

The ABS estimates that the average insured value of a house (replacement value and contents) in Queensland is approximately $C_i=\$320,000$ in 2010 Australian dollars. The number of alterations and new houses increases linearly by 2100 to 106,000, 124,000, 60,000 and 1,850,000 for Cairns, Townsville, Rockhampton and Brisbane, respectively, or 2.1 million in total. The value of new housing from 2010 exceeds \$360 billion.

4. WIND VULNERABILITY

A wind vulnerability function expresses building damage and contents loss as a function of wind speed. In Australia, a widely used wind vulnerability model for North Queensland is that proposed by Walker (1994) based on insurance industry experience. Considered to be the best available model at the time, the wind vulnerability model has been used by Harper (1999), Stewart (2003), Waters et al. (2010), and others. More recently, a suite of vulnerability curves is being developed (Wehner et al. 2010). Many of these curves are proprietary, however, some details are described by Wehner et al. (2010) and Ginger et al. (2010). There is uncertainty and variability of wind vulnerability, however, since no data or methodology is provided to estimate this uncertainty we assume that (i) there is full confidence about the wind speed to cause negligible and maximum damage (i.e. variability of damage is zero), (ii) that the variability increases linearly with wind speed and reaches a maximum when vulnerability is 50%. Wind vulnerability functions are:

$$\text{Pre-1980 Construction: } \text{Vul}(v) = 20 \left(\frac{K_t K_s v}{30} - 1 \right)^2 + 50 \left(\frac{K_t K_s v}{30} - 1 \right)^6 + \text{CI} \quad \frac{K_t K_s v}{30} > 1 \quad (2)$$

$$\text{AS4055-2006: } \text{Vul}(v) = 100 \left\{ 1 - \exp \left[- \left(\frac{K_t K_s v}{e^\beta} \right)^{\frac{1}{\alpha}} \right] \right\} + \text{CI} \quad \text{Vul}(v) \leq 100\% \quad (3)$$

where α and β are parameters that describe the shape and position of the curve (Stewart and Wang 2011), K_t is given in Table 1, $K_s=0.80$, and CI is the normally distributed uncertainty with mean equal to zero and the 90th percentile confidence interval is 20% when $\text{Vul}=50\%$. The pre-1980 vulnerability curve will be used for pre-1980 housing in cyclonic regions of Queensland (Cairns, Townsville, Rockhampton), and the vulnerability curves C1 and C2 will be used for post-1980 housing in these cyclonic regions. For non-cyclonic regions (Brisbane), the improvement of building standards is less clear and so vulnerability curve N2 will be used for all existing and new housing. It is clearly acknowledged by Ginger et al. (2010) that since the wind vulnerability curves were obtained from expert opinion they need to be validated with reliability data. Figure 2 shows mean and 5th and 95th percentile losses for pre-1980 construction and AS4055-2006 Wind Classifications N2, C1, C2 and C3.

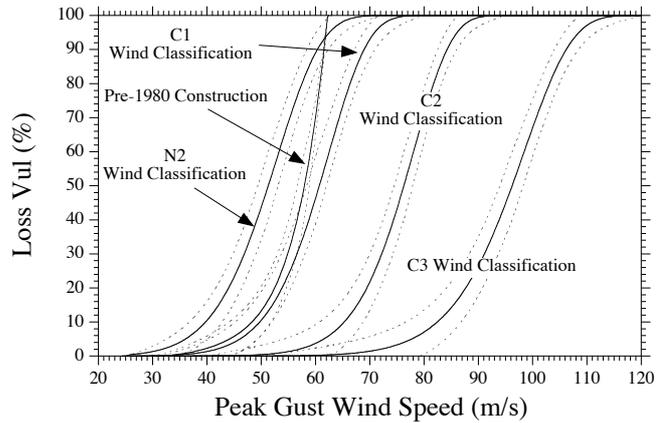


Figure 2. Mean and 5th and 95th Percentile Wind Vulnerability Curves.

5. CLIMATE ADAPTATION STRATEGY: STRENGTHEN NEW HOUSING

The adaptation strategy considered herein is to design new houses to enhanced design codes. In this case, increasing the current AS4055-2006 wind classification by one category (see Table 1). This means that new construction and alterations would be designed to resist 50% higher wind pressures. Designing new houses to these enhanced wind classification will reduce vulnerability often by more than 80% (Stewart and Wang 2011). The increase in cost of a new timber house due to an increase in design wind class is approximately \$2,500, \$3,700 and \$4,200 per house for increases in wind classification N2 to C1, C1 to C2 and C2 to C3, respectively (AGO 2007). These increases gives C_{adapt} of 1-2.5% of the value of the house. These costs arise from larger structural members for the roof frame, wall frame, wall bracing, and foundations, as well as stronger fixings.

The annual insured damage risk in terms of percentage damage $D(t)$ in year t caused by a wind hazard is

$$D(t) = \int \text{Vul}(v) f_v(v,t) dv \quad (4)$$

where $\text{Vul}(v)$ is the vulnerability function that defines wind damage as a function of wind speed (see Figure 2) and $f_v(v,t)$ is the time-dependent probability density function for annual maximum wind speed derived from Eqn. (1). Equation (4) assumes that damage is caused by the largest wind event in any calendar year.

Two criteria will be used to assess the cost-effectiveness of adaptation strategies:

1. Net Present Value (NPV)
2. Probability of cost-effectiveness or $\text{Pr}(\text{NPV}>0)$

The net benefit or net present value (NPV) up to year T is $\text{NPV}(T) = \text{PV}_0(T) - \text{PV}_a(T)$ where $\text{PV}_0(T)$ is the 'business as usual' or 'do nothing' present value at time T where future new buildings are built according to current standards and there are no climate adaptation strategies to reduce the impact of wind damage, and $\text{PV}_a(T)$ is the present value (sum of damage and adaptation costs) with implementation of the adaptation strategy. All costs are discounted to present values. If implementation of an adaptation strategy leads to a PV that is lower than one for the 'business as usual' or 'do nothing' PV, then $\text{NPV}>0$. It shows that there is a net benefit and so the adaptation measure improves efficiency (OBPR 2010).

Monte-Carlo simulation analysis is used as a computational tool to propagate uncertainties through the cost-benefit analysis, although analytical methods could also be used (e.g., Stewart and Melchers 1997). Since wind speed and vulnerability are random variables, the simulated NPV is also a stochastic variable. This allows 10th and 90th percent lower and upper bounds of NPV to be calculated, as well as the probability that an adaptation measure is cost-effective denoted herein as Pr(NPV>0).

5.1. Business as Usual (Do Nothing)

The expected cumulative damage costs starting at 2010 and extending to year T expressed in dollars is

$$PV_0(T) = \sum_{t=2010}^T \sum_{j=1}^2 \frac{[N_{pre,j}(t)D_{pre,j}(t) + N_{post,j}(t)D_{WC,j}(t)]C_1}{(1+r)^t} \quad (5)$$

where $D_{pre,j}(t)$ and $D_{WC,j}(t)$ are the damage risk associated with pre-1980 construction and current wind classification, $N_{pre,j}(t)$ and $N_{post,j}(t)$ are the cumulative numbers of houses constructed to pre-1980 and post-1980 standards in a city to year t, j indicates exposure (foreshore or non-foreshore), r is the discount rate, and C_1 is the insured value of a house. A climate-change induced increase in wind speed will increase annual damage risks and so increase PVs.

5.2. Adaptation Strategy

The cumulative NPV for the adaptation strategy of designing new houses to enhanced design codes is

$$NPV(T) = \sum_{t=t_{adapt}}^T \sum_{j=1}^J \frac{\left[\sum_{t_1=t_{adapt}}^t N_{new,j}(t_1) (D_{WC,j}(t) - D_{WC+1,j}(t)) - \frac{C_{adapt}}{C_1} N_{extra,j}(t) \right] C_1}{(1+r)^t} \quad (6)$$

where C_{adapt} is the cost of the adaptation strategy, t_{adapt} is time of implementing the adaptation strategy, $N_{new,j}(t)$ is the cumulative number of alterations and new housing to time t, $N_{extra,j}(t)$ is the annual number of alterations and new housing, and $D_{WC+1,j}(t)$ is the annual damage risk associated with increasing the current wind classification by one category. The benefit of strengthened new housing is the reduction of damage of new and alteration housing, which is independent of the mix of existing housing stock.

Note that the damage risks and losses calculated herein are based on a city 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 city would have higher damage risks and others lower even though they may both be located in the same broad exposure category used herein. Moreover, the analyses conducted herein are primarily aimed at assessing the comparative effects of possible climate change scenarios, and the wind and vulnerability models used for comparative analyses is instructive and suitable for initial climate impact and adaptation screening.

6. RESULTS

Results are calculated using Monte-Carlo event-based simulation methods. Unless notified otherwise the discount rate is 4% and the date of implementing adaptation strategies is 2011. The ‘business as usual’ (no adaptation) cumulative mean present values of damage $PV_0(T)$ given by Eqn. (5) show that the cumulative PV of damage can reach \$6.8 billion, \$10.0 billion, \$15.8 billion and \$23.1 billion dollars by 2100 for Brisbane, for no change, moderate change, significant change and poleward shift climate scenarios, respectively. These losses increase by a further 15% if damages to Cairns, Townsville and Rockhampton are added to Brisbane losses. There is clearly a high likelihood of large potential economic losses and suggest that climate adaptation strategies are needed to ameliorate these losses.

Figures 1 and 3 show the mean and 10th and 90th percentile values NPV. Results show that for an adaptation cost of \$3,700 per new house in Brisbane, total adaptation costs will reach \$2.2 billion by 2100, but will reduce mean wind losses by nearly \$8 billion by 2100 for a climate scenario of 20% increase in wind speed by 2100 (significant change). Hence, the mean total NPV or net benefit ranges from \$2.3 to \$8.3 billion dollars by 2100 for different climate scenarios. Figure 3 shows that implementing the adaptation strategy in Brisbane accounts for more than 90% of total benefits. The distribution of NPV is highly non-Gaussian which suggests that Monte-Carlo methods are well suited to this type of analysis (Stewart and Wang 2011).

Figure 1 shows how NPV varies with time. While adaptation costs flatten out over time due to discounting, the benefits continue to increase with time since the vulnerability of total housing stock is gradually being reduced due to increasing numbers of new housing with reduced vulnerability and so the NPV accrues over time. It is evident from Figure 1 that benefits exceed adaptation costs after approximately 2030 to 2050.

If there is significant climate change or a poleward shift in cyclonic activity to Brisbane by 2100 then the probability of a net benefit exceeds 97% so there is nearly full surety that the adaptation strategy is cost effective. Most of the benefit of adaptation strategies comes from Brisbane due to its large population. The probability that the adaptation strategy results in a net benefit is reduced to 68.5% for Cairns, for significant change by 2100. This shows that while mean NPV may be high, there is still some likelihood that NPV is less than zero caused by wind speed variability that results in few damaging cyclones. If there are few damaging cyclones then the benefits of adaptation strategies are minimised, but the cost of adaptation remain.

There may be economic and political benefits in deferring implementation of a climate adaptation strategy. If timing of adaptation is deferred to 2020, 2030 or 2050 that the NPV reduces, but that $\text{Pr}(\text{NPV}>0)$ is not overly sensitive to adaptation timing for significant change or poleward shift climate scenarios (Stewart and Wang 2011). The reason is that the effects of adverse climate change will become most evident later in the century, so a delay in implementing an adaptation strategy may result in immediate savings in adaptation costs, but will not increase damage costs significantly in the short term. To be sure, the benefits of adaptation strategies are maximised if they are implemented promptly, but deferring these adaptation strategies to 2020 or even 2030 will still result in a net benefit to society, albeit at a reduced level when compared to immediate implementation.

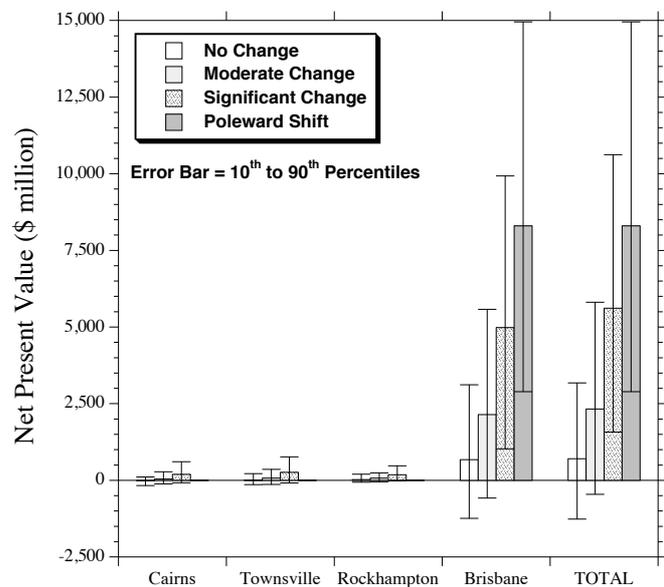


Figure 3. Mean and 10th and 90th percentile Net Present Values at 2100.

Table 2 shows the mean NPV per new house constructed by 2100 (mean NPV divided by cumulative total of new houses built by 2100). The savings of adaptation for each new house built is highest for Brisbane.

Table 2. Mean Net Present Value Per New House.

Location	Mean NPV per New House (\$/New House)			
	No Change	Moderate Change	Significant Change	Poleward Shift
Cairns	-\$62.1	\$391.3	\$1,809	-
Townsville	\$54.4	\$554.7	\$2,099	-
Rockhampton	\$428.1	\$1,157	\$3,060	-
Brisbane:	\$470.6	\$1,177	\$3,077	\$4,547

The results are not particularly sensitive to changes in key variables. For example, if the adaptation costs are increased by 50% then total NPV reduces from \$5.6 billion to \$4.5 billion, and $\text{Pr}(\text{NPV}>0)$ reduces from 97.5% to 91.2%, for significant change by 2100. Other climate adaptation strategies were considered. We found that retrofitting 1,000 older houses per year to current standards in each city is a more costly adaptation strategy which resulted in total mean NPV of -\$529 million for significant change, with 98.5% likelihood of a net loss. Strengthening pre-1980 houses to current standards immediately after they experience cyclone damage resulted in a mean total NPV of only \$15.5 million [$\text{Pr}(\text{NPV}>0)=5.8\%$] and \$70.8 million [$\text{Pr}(\text{NPV}>0)=16.5\%$], for moderate and significant change by 2100. These adaptation strategies are clearly inferior to the potential billion dollar benefits predicted for the adaptation strategy studied herein.

Finally, it is interesting to note that if there is no change in climate then Brisbane will experience a mean NPV of \$676.6 million with 53.4% likelihood that this benefit will occur. In other words, even if there is no climate change there is a greater than 50-50 chance that investments in climate adaptation will still lead to a net benefit which makes sense as a 'no regrets' or 'win-win' policy even if climate predictions are inaccurate.

Full details and results for NPV, $\text{Pr}(\text{NPV}>0)$ and Benefit-Cost Ratio (BCR), including the sensitivity of results to discount rate, CI, C_{adapt} , etc., are described by Stewart and Wang (2011).

7. DISCUSSION AND CONCLUSIONS

The economic viability of a climate adaptation strategies were assessed using a probabilistic risk-based framework that considered the effect uncertainty of wind vulnerability of houses, costs of adaptation, timing of adaptation, discount rates, future growth in new housing and time-dependent increase in wind speeds. Increasing the wind classification for design of new construction for all locations will have modest adaptation costs and by 2100 produce benefits exceeding \$8.3 billion if there is a poleward shift of cyclones towards Brisbane. Clearly, increasing the design wind classifications in the Australian Standard AS4055-2006 for all new housing shows great promise as a cost-effective climate adaptation strategy. The benefits are highest for Brisbane due to its large population and high vulnerability of existing residential construction. Hence, increasing the wind classification for new housing in Brisbane from Wind Classification N2 to C1 at a cost of \$3,700 per house is highly cost-effective and efficient with 80-100% likelihood that a net benefit can be achieved by 2100. The NPV will increase if other direct and indirect costs of housing damage are included.

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