Assessing the impacts of tropical cyclones

Using Darwin as a test case, Craig Arthur, Anthony Schofield and Bob Cechet assess the benefits of Geoscience Australia's Tropical Cyclone Risk Modelling tool in assessing the potential impact of a tropical cyclone.

Abstract

Tropical Cyclone (TC) Tracy impacted Darwin early on Christmas Day, 1974, resulting in 71 deaths, the destruction of thousands of homes and the evacuation of over 35000 people. Several factors contributed to the widespread destruction, including the intensity of the cyclone, vegetation overhanging buildings and construction materials employed in Darwin at the time. Since 1974, the population of Darwin has grown rapidly, from 46000 to nearly 115000 in 2006. If TC Tracy were to strike Darwin in 2008, the impacts could be catastrophic. However, tools such as Geoscience Australia's Tropical Cyclone Risk Model (TCRM) could be used to allow emergency managers to plan for such a scenario.

We perform a validation of TCRM to assess the impacts TC Tracy would have on the 1974 landscape of Darwin, and compare the impacts to those determined from a post-impact survey. We find an underestimate of the damage at 36% of replacement cost (RC), compared to survey estimate of 50–60% RC. Some of this deficit can be accounted for through the effects of large debris. Qualitatively, TCRM can spatially replicate the damage inflicted on Darwin by the small cyclone, identifying localised areas of increased damage.

For the 2008 scenario, TCRM indicates a nearly 90% reduction in the overall damage (% RC) over the Darwin region. Once again, the spatial nature of the damage is captured well, with the greatest damage inflicted close to the eye of the cyclone. Areas that have been developed since 1974 such as Palmerston suffer very little damage due to the small extent of the severe winds. The northern suburbs, rebuilt in the years following TC Tracy, are much more resilient, largely due to the influence of very high building standards in place between 1975 and 1980.

Introduction

Tropical Cyclone (TC) Tracy developed northeast of Darwin on 20 December 1974, intensified and progressed slowly in a south-westerly direction until December 23, when it rounded Bathurst Island and tracked directly towards Darwin. TC Tracy crossed the Darwin coast just after 3:30 AM on 25 December. The peak wind gust recorded at Darwin Airport was 217 km/h shortly before the anemograph failed, however it is estimated that the peak winds were over 250 km/h. Corrected pressure readings from the mercury barometer at the Bureau of Meteorology regional office recorded a minimum pressure of 950 hPa. Within 24 hours of landfall, wind speeds had dropped below gale force, giving a TC lifetime of four days (Bureau of Meteorology, 1977).

TC Tracy resulted in 71 deaths and an estimated 650 injuries. In the days following the impact, over 35000 of Darwin's population of 47000 were evacuated from the city, constituting the largest ever evacuation operation in Australia. The magnitude of the impact was such that this event still remains as one of the most destructive natural disasters in Australia's history.

Damage to property caused by TC Tracy was extensive, owing largely to the path of the cyclone directly through Darwin. A survey of damage conducted in the aftermath of TC Tracy revealed over 52% of houses were completely destroyed, and many more suffered a high level of damage (Walker 1975). It is suggested that 80% of residential buildings were either destroyed or rendered uninhabitable (Stretton, 1975). Walker (1975) interpreted the loss of roof cladding to be a major cause of extreme damage, resulting in a significant loss of structural strength and damaging debris effects.

Developed by Geoscience Australia, the Tropical Cyclone Risk Model (TCRM) is a statistical model of tropical cyclone activity which is used to assess hazard and risk associated with tropical cyclones (Arthur et al. 2008). TCRM can also be used to simulate individual scenarios in order to estimate the impact of severe winds on a community. In this paper, we describe the application of TCRM to a scenario of TC Tracy impacting the present day residential building stock of Darwin, and compare this to the estimated and observed damage for the actual impact in 1974.

The first step in estimating the impact of a TC on a community is to estimate the maximum wind speed experienced during the passage of the storm. We use TCRM to generate a regional wind field, which excludes local influences on the wind speed. The regional wind speeds are modified for local effects such as topography, land-use classification and shielding from surrounding structures. Local wind speeds are then related to residential building damage through vulnerability curves, which provide an estimate of the loss (as a percentage of replacement cost) amongst a population of buildings given an incident wind speed.

Here we focus on spatially defining the level of damage inflicted, which can provide emergency managers with invaluable information such as where to deploy resources in a recovery operation. We also restrict the analysis to residential buildings only. We draw comparisons between surveyed damage and the modelled damage for the impact in 1974, and then extend the analysis to determine the potential impact on the present-day landscape of Darwin.

Wind field modelling process

Although it is possible to generate synthetic TC tracks within TCRM, this investigation uses the 'best track' of TC Tracy recorded in the Bureau of Meteorology tropical cyclone best track database (Trewin and Sharp 2007). Wind field simulations are undertaken as a two-stage process within TCRM. To reflect the behaviour of real-world TCs, a radial wind profile model is used to construct a symmetric, gradient-level wind field. This gradient wind field is then modified by a boundary layer model that incorporates the asymmetric distribution of winds in a moving tropical cyclone, providing a regional estimate (1 km horizontal resolution) of the winds associated with the cyclone.

To incorporate the influences of terrain, topography and shielding from structures, wind field multipliers based on the site-specific factors described in the Australian/New Zealand Wind Loading Standard (AS/NZS 2002) are applied to modify the regional wind field. These are simple multiplicative factors, derived at a resolution of 25 m, are directionally dependent and are pre-calculated for ease of use. As the urban footprint of Darwin has increased dramatically since 1974, the multipliers have determined for both the 1974 and present-day Darwin landscapes. The resulting modelled wind fields represent the maximum three second gust wind speed predicted for a location over the lifetime of the event.

TCRM uses a 2-dimensional model of the wind field associated with a tropical cyclone. While it is a parametric model, it retains sufficient detail to reproduce many features of a TC wind field. The 2-dimensional model allows the wind field to be quickly simulated at a resolution that would not be feasible in a full 3-dimensional atmospheric model. TCRM can also be applied in situations where there are few observations to constrain a fully 3-dimensional model.

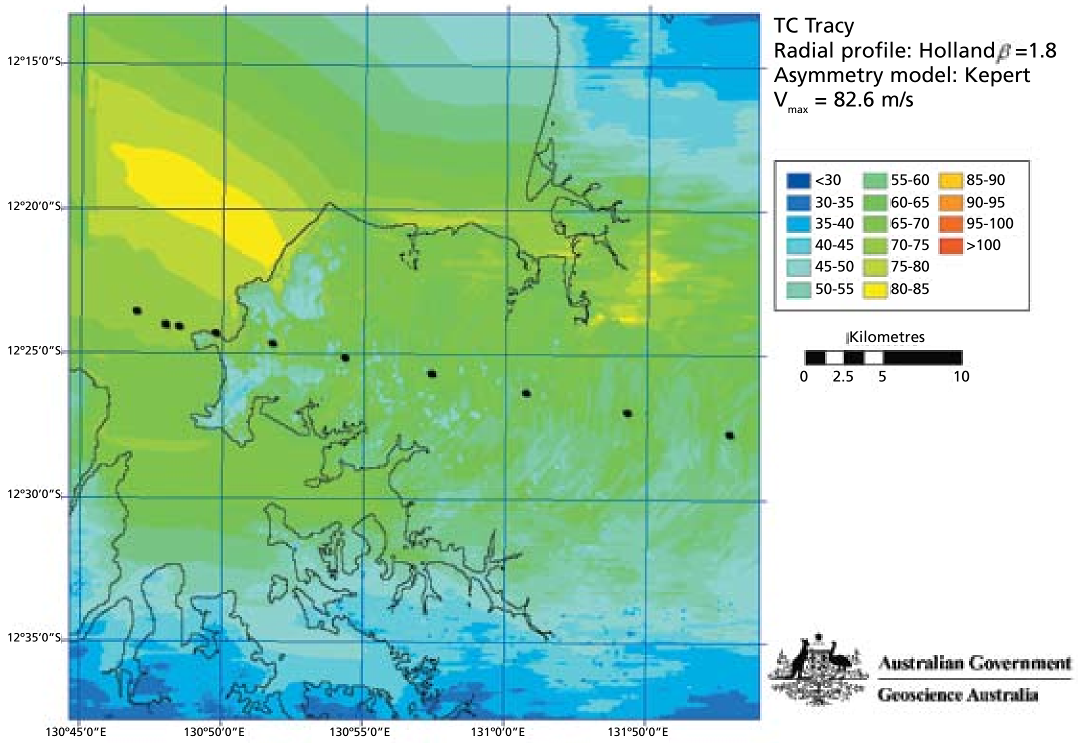
Several options for radial wind profiles and boundary layer models are available to users including the profiles of Schloemer (1954), Jelesnianski (1966), Holland (1980), McConochie et al. (also referred to as double Holland; McConochie et al. 2004), Willoughby et al. (2006), and a Rankine vortex. Boundary layer models include those of Kepert (2001), Hubbert et al (1991) and McConochie et al (2004). Users can select any combination of radial and boundary layer models at run time.

TC Tracy poses a significant challenge to wind field modelling due to the unusual characteristics of the cyclone. TC Tracy remains one of the smallest tropical cyclones on record, with a radius of gale force winds of less than 50 km. The radius of maximum winds (RMW) at landfall was only 8 km. The central pressure at landfall is estimated to have been 950 hPa, which together with the small diameter, yields a pressure gradient of 5.5 hPa/km (Bureau of Meteorology, 1977). This value is unusually high, and results in a radial wind profile which has a sharp peak and a rapid decay outside the RMW.

To simulate TC Tracy, we use the Holland (1980) profile and the Kepert boundary layer model (2001). The Holland model was developed using data obtained from TC Tracy, and provides the best representation of the sharp peak in winds near the RMW. The Kepert boundary layer model was selected owing to the incorporated gradient-to-surface wind reduction (which is necessary when the Holland model is employed, as it estimates a gradient level wind; Harper 2002), and the success of this model in replicating the wind field of TC Larry (Edwards et al. 2007). The resulting model produced a maximum gust wind speed of 72 m.s-1 (260 km/h) at the Darwin Airport anemograph site, agreeing well with estimates of the maximum wind speed (Bureau of Meteorology, 1977).

TCRM's parametric wind field is a regional estimate of the surface wind speed associated with a tropical cyclone—nominally at 1 km resolution—and does not account for the land-use classification, topography or buildings. To incorporate the effects of flow over these features, we apply wind field multipliers, based on the site-specific factors described in the Australian/New Zealand Wind Loading Standard (SA/SNZ 1170.2:2002). These have been calculated in a GIS framework at a horizontal resolution of 25 metres (50 metres for the 1974 simulation). The resulting local wind field for 1974 is shown in Figure 1.

Figure 1: Estimated maximum wind speed from TC Tracy in 1974, incorporating site-specific influences on the wind speed arising due to topography, terrain and existing structures.



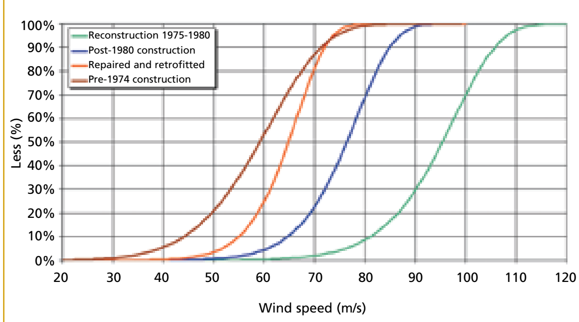
Wind speeds over the northern suburbs of Darwin exceed 75 m.s-1 (270 km/h) near the outskirts of built-up areas and close to the coastline. On the southern side of the cyclone's path, peaks winds in the southern suburbs are in the range of 40—50 m.s-1 (145—180 km/h).

Damage modelling

Damage to residential structures is estimated by utilising a suite of vulnerability curves, appropriately selected for the class of building present in the region of interest (Figure 2). The population of structure types in Darwin and the standards to which they are built are significantly different between 1974 and 2008, due to the reconstruction of structures following TC Tracy and the revision of building codes with time (Nicholls, 2007).

The vulnerability relations have been derived through a series of wind vulnerability workshops conducted by Geoscience Australia (Timber ED Services, 2006). The relations were developed by consultation with wind engineers and are based predominantly on engineering judgement of the damage incurred as a percentage of replacement cost (% RC) at various incident wind speeds. We make two key assumptions about the vulnerability relations: (1) the differences in the vulnerability relations are representative of the changes in building standards over time and (2) all buildings in each class are identical and perform (under wind loading) in line with the

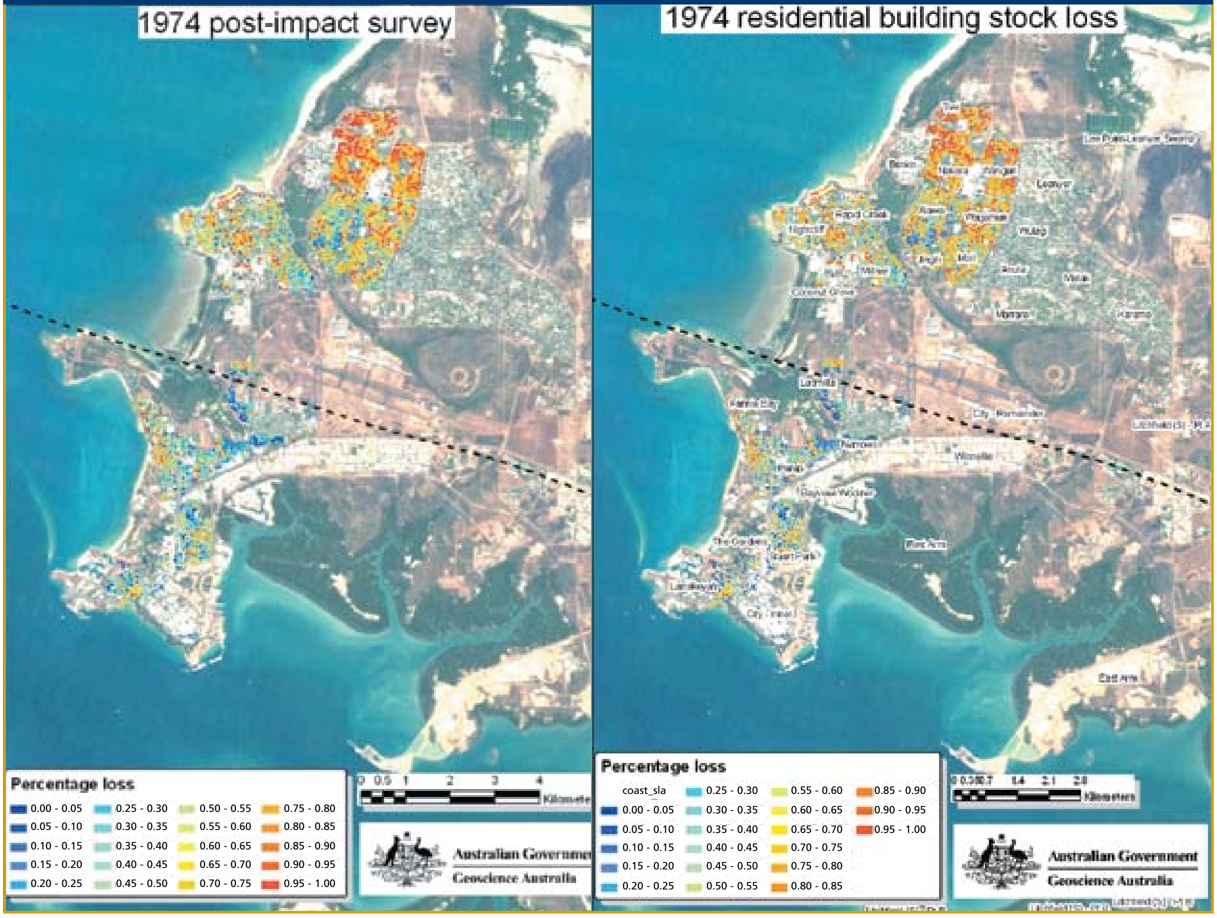
Figure 2: Comparative mean damage model curves for building classes present in Darwin for the 2008 analysis.



appropriate relation. Each vulnerability relation contains three functions, providing not only a mean estimate of the loss for a building population, but upper and lower confidence limit estimates of the range of loss amongst that population.

Information on building age and location for the 2008 scenario is provided by Geoscience Australia's National Exposure Information System (NEXIS), a nationally consistent spatial database of building exposure (Nadimpalli et al. 2007). For the 2008 analysis, residential structures are classified into four groups based on age. No classification on construction type was performed.

Figure 3: Post-TC Tracy impact survey damage estimates (left) and estimated mean residential building stock loss (% RC) for Darwin in 1974 based on individual building analysis (right).



These four classes are:

1. Pre-1974: these are structures which survived effectively undamaged during TC Tracy. This is based on the behaviour of timber-framed high-set fibro-clad housing;
2. Repaired and retrofitted: these are structures which survived TC Tracy with a low proportion of damage (≤40% RC);
3. 1975—1980: This class includes all structures that sustained over 40% RC damage during TC Tracy, and are assumed to have been demolished and rebuilt prior to 1980, as well as new (additional) structures built between 1975 and 1980; and
4. Post-1980: buildings constructed after 1980.

Two methodologies are used to calculate the loss (% RC) associated with the impact of TC Tracy. For both approaches, we first apply the damage curves over the entire region for which site-specific wind speeds were calculated, providing a raster image of the estimated population damage for each class of building. For the first method, we extract from this raster the values corresponding to the location of buildings in the dataset being examined. This allows a direct comparison between the surveyed damage and the estimated damage from TCRM.

The second approach is applied for the 1974 and 2008 building stock and, due to availability of data in NEXIS, relies on meshblock areas over the Darwin region. Meshblocks are a statistical subdivision of census districts, and contain up to approximately 30 residential structures. There are some 335 meshblocks in the Darwin area that contained buildings that were surveyed in the aftermath of TC Tracy. To estimate the damage using meshblocks, we take the mean estimated wind speed over the area of the block and apply the suite of vulnerability relations. The estimated damage for the meshblock is calculated as a mean of the vulnerability relations, weighted by the number of each building type in the meshblock. For the 1974 analysis, we determine the damage for the pre-1974 class of buildings only.

While the meshblock analysis does not provide information on the damage inflicted to individual buildings, it does provide quantitative information on the likelihood of significant damage to small areas within a community. Emergency managers preparing for, or recovering from, an impact can use such information to guide the deployment of resources or identify areas that may require evacuation before the onset of gale-force winds.

Figure 4: Estimated mean residential building stock loss (% RC) for Darwin in 1974 using the meshblock methodology.

1974 analysis

Surveys undertaken in the months following impact show that TC Tracy inflicted significant damage across the northern suburbs such as Nakara and Wanguri, with the majority suffering major damage or complete destruction (Halpern Glick Pty. Ltd., 1975). Walker (1975) attributes some of this to the poor resilience of newer roofing materials to sustained loading induced by the severe winds. The failure of roofing materials generated large debris (e.g. entire roof structures), which then caused significant damage to downwind buildings. This may in part explain the relative spatial uniformity of damage through the northern suburbs. On the basis of the survey, the mean damage in Darwin is estimated at 56% RC, however uncertainties in the data mean this figure is in the range of 50—60% RC.

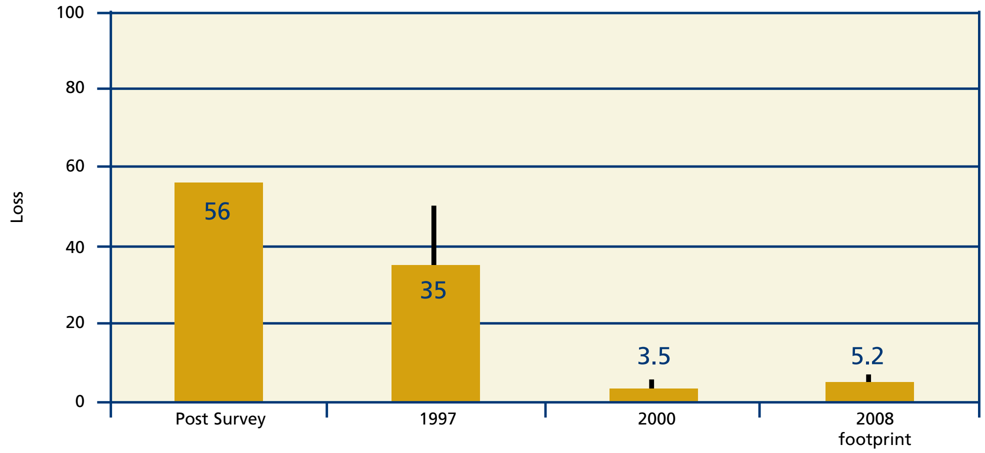
The location of buildings provided in the survey data is used to extract damage estimates from the TCRM simulation. Our results show greater damage over the suburbs of Nightcliff and Rapid Creek compared to the survey results (Figure 3). The difference is in part due to the proximity of these suburbs to the coastline and hence higher site wind speeds. The northern suburbs of Nakara and Wanguri show less damage compared to the survey—most notably only buildings near the outskirts of the suburbs suffer significant damage. Using the 1974 damage model, the mean predicted loss for the city of Darwin during TC Tracy in 1974 is estimated at 35% RC (5th percentile: 17% RC, 95th percentile: 50% RC) of the replacement cost for residential buildings.

The meshblock analysis produces almost identical results to the individual building analysis, with a mean loss of 36% RC (5th percentile: 18% RC, 95th percentile: 52% RC) (Figure 4). Spatially, the results are also very similar, with meshblocks on the outskirts of built-up areas suffering higher damage than those in the interior. Areas along the track of the storm (e.g. Ludmilla) suffer significant damage, while areas to the south of the track (e.g. Stuart Park and Larrakeyah) suffer the least damage.

TC Tracy was remembered for the levels of complete destruction over many parts of Darwin. The effect of destruction of residential buildings and vegetation is to decrease the level of shielding afforded to adjacent buildings and a coincident increase in the site wind speed. In applying the wind field multipliers (AS/NZS 2002), we have throughout assumed the shielding values remain static during the passage of the TC. In the case of the 1974 impact, the complete destruction of buildings may result in the value of the shielding

Figure 5: Estimated mean residential building stock loss (% RC) for Darwin in 2008 using the meshblock methodology.

Figure 6: Mean damage (% RC) associated with TC Tracy determined from the post-impact survey, TCRM analysis for 1974, TRCM for 2008 and TCRM for 2008 (using only the 1974 urban footprint). Black vertical bars indicate the range of the 5th and 95th percentile.



multiplier (Ms) approaching unity, in turn increasing the site wind speed and the resulting damage inflicted on buildings that would normally have significant shielding. We surmise that this dynamic shielding effect may account for a significant portion of the shortfall in damage for the 1974 simulation.

2008 analysis

For the 2008 analysis, we use the meshblock methodology to determine the damage incurred. Additionally, the wind field multipliers are updated for the terrain and shielding classifications for the modern landscape of Darwin.

One of the most significant changes to Darwin between 1974 and 2008 is the population. From 47,000 prior to TC Tracy, Darwin is now home to around 115,000 people. In the intervening years, there have also been significant changes to the building standards employed in the city (Nicholls 2007) affecting the resilience of residential buildings. Because of these changes, approximately 1% of the buildings in present-day Darwin remain unchanged from 1974. Over one third were repaired and retrofitted while nearly half the current building population were built to the very high standards that existed between 1975 and 1980 (Nicholls 2007).

A cyclone identical to TC Tracy impacting Darwin in the present day landscape would result in losses of 3.5% RC (5th percentile: 1.8% RC, 95th percentile: 5.2% RC; Figures 5 and 6). These results reflect a 90% reduction in mean losses compared to the 1974 analysis. In contrast to the 1974 simulation, the improved building standards mean there would be a vast reduction in the number of buildings suffering complete destruction. This has the effect of minimising the dynamic shielding effect and local increases in site wind speed.

Much of the reduction in damage in the modern day scenario can be attributed to changes in building vulnerability in the intervening years. However, some of this reduction is almost certainly due to the growth of the urban footprint of Darwin. The small size of TC Tracy results in destructive winds affecting only a small proportion of the residential building stock in present-day Darwin. To isolate the influence improved building standards have made, the present-day damage is calculated only for those meshblocks identified as containing residential structures in 1974. Based on this, damage is estimated to be 5.2% RC (5th percentile: 2.6% RC, 95th percentile: 7.7% RC; Figure 6). This figure is likely to be a better representation of the improvements to building vulnerability.

Conclusions

The results presented here indicate both the wind field and damage generated by TC Tracy in 1974 are well replicated using the TCRM. The spatial distribution and magnitude of wind-related damage is well captured, allowing emergency managers to identify likely areas of significant damage at the suburb level. Based on the accurate modelling of the impact of TC Tracy, we believe that TCRM is a valid tool for examining the impacts of an identical storm in the present-day environment. The workflows outlined here are also able to be directly applicable to other historical TC events or future scenarios.

The TCRM can be used to identify areas likely to suffer significant severe wind damage due to the impact of a tropical cyclone, providing invaluable information to emergency managers involved in the preparation and recovery phases. Quantitative differences between the observed damage and estimated damage using TCRM can in part be accounted for by inclusion of large debris-induced damage.

The design of TCRM, which allows users to apply a range of radial profiles and boundary layer models, permits a probabilistic approach to impact assessments. Because TCRM uses a parametric model of the tropical cyclone wind field, impact scenarios can be assessed rapidly allowing emergency managers to make better informed decisions in a timely manner. A set of pre-calculated scenarios may also be of great benefit to emergency managers for training and demonstration purposes.

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