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Estimating Tropical Cyclone wind-induced losses using very high resolution Numerical Weather Prediction

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ABSTRACT

On the 20th February 2016 TC Winston made landfall in Fiji causing substantial damage to buildings and local infrastructure. 44 people were killed, over 50,000 people evacuated and an estimated US$1.0 billion of damage was done (Esler, 2017). Events such as these require accurate forecasting of the storm strength, storm track, timing and lifespan to aide preparedness and to mitigate against possible damage and loss.

Today's supercomputers are now capable of running Numerical Weather Prediction (NWP) models at horizontal resolutions that allow for explicit representation of key atmospheric processes and resolve the often complex terrain that the Pacific Islands possess in a timely manner. Here we describe work that looks at how well a modern NWP model running with horizontal resolutions of 1.5 km down to 100 m can forecast an event such as TC Winston and conduct an initial study into how NWP model output can be used to estimate the likely wind-induced infrastructure damage.

1. Introduction

Only in recent years, with ever-improving supercomputer resources, have Numerical Weather Prediction (NWP) models begun to be run at resolutions that explicitly resolve the wind flow interactions over complex terrain. Now, supercomputing resources are such that fine-scale NWP on scales O(100 m) is very possible and we can begin, for example, to use these models to confidently simulate the processes, lifecycles and impacts of tropical cyclones.

TC Winston is considered the costliest cyclone in South Pacific history with a central low pressure minimum of just 915 hPa and 10-minute sustained winds of 230 kph (~63 m/s) (see https://en.wikipedia.org/wiki/Cyclone_Winston and references therein). The passage of the eye of TC Winston over Vanua Balavu, Fiji provides a recent case where such fine-scale NWP can be tested.

Using the UK Met Office Unified Model (hereafter UM, see descriptions in Webster *et al.* (2003) and Davies *et al.* (2005)) as the chosen NWP model, we present the results of work investigating how well modern NWP models, run at horizontal resolutions approaching 1 km and higher, can simulate an event such as TC Winston, the effects that ancillary data such as high resolution terrain data can have on the simulations and attempt to apply the modelled wind fields to the RiskScape (see Schmidt *et al.* (2011)) natural hazard impact and loss tool to assess the likely built infrastructure and economic losses TC Winston would have caused. Comparison against observed meteorological observations will be made too.

2. The NWP Model

The UM is a state-of-the-art NWP model now widely used by many national meteorological centres around the world, and collaboratively developed under the guidance of the Unified Model Partnership. NIWA is a member of this Partnership and uses the UM as the primary tool in its EcoConnect hazard forecasting system with output from the UM used to drive many downstream models covering hydrology, storm surge and wave forecasting applications, and is run in two configurations; a 12 km resolution New Zealand Limited Area Model (NZLAM) set up that covers the New Zealand and wider Tasman area including the eastern Australia coastal region, and the 1.5 km resolution convection-permitting New Zealand Convection-Scale Model (NZCSM).

In this work, a one-way nested configuration of the UM is used whereby a Global configuration of the UM with ~23 km horizontal resolution at tropical latitudes is used to generate lateral boundary conditions for a 1.5 km configuration of the UM centred on Fiji using a 600 × 600 × 70 domain. This model is run for 48 hours and in turn is configured to generate initial and lateral boundary conditions for higher resolution configurations of the UM, down to ~100 m. From each UM forecast, meteorological fields are output to enable qualitative comparison against available satellite imagery and quantitative verification against available ground-based observations.

Where available, land use and terrain data is sourced from the IGBP (IGBP, 1990), CCI (ESA, 2017), GLOBE (Globe Task Team *et al.* (1999)) and Shuttle Radar Topography Mission (USGS, 2004) projects respectively.

3. Simulating TC Winston

Being able to forecast the track, central pressure and associated wind speeds of a Tropical Cyclone would greatly assist in preparing for the arrival of the storm and, after the event, assist in the planning of damage surveys and better understanding how the built infrastructure was affected.

From a forecast started at midnight UTC on the 19th February 2016, Figure 1 shows the forecast size, location and associated wind speeds of TC Winston as it approaches the island of Fiji at 0500 UTC on 20th February 2016 from the 1.5 km model. The size and location of the modelled storm can be qualitatively compared to the Himawari 8 cloud top temperature imagery in the right panel for the same time.

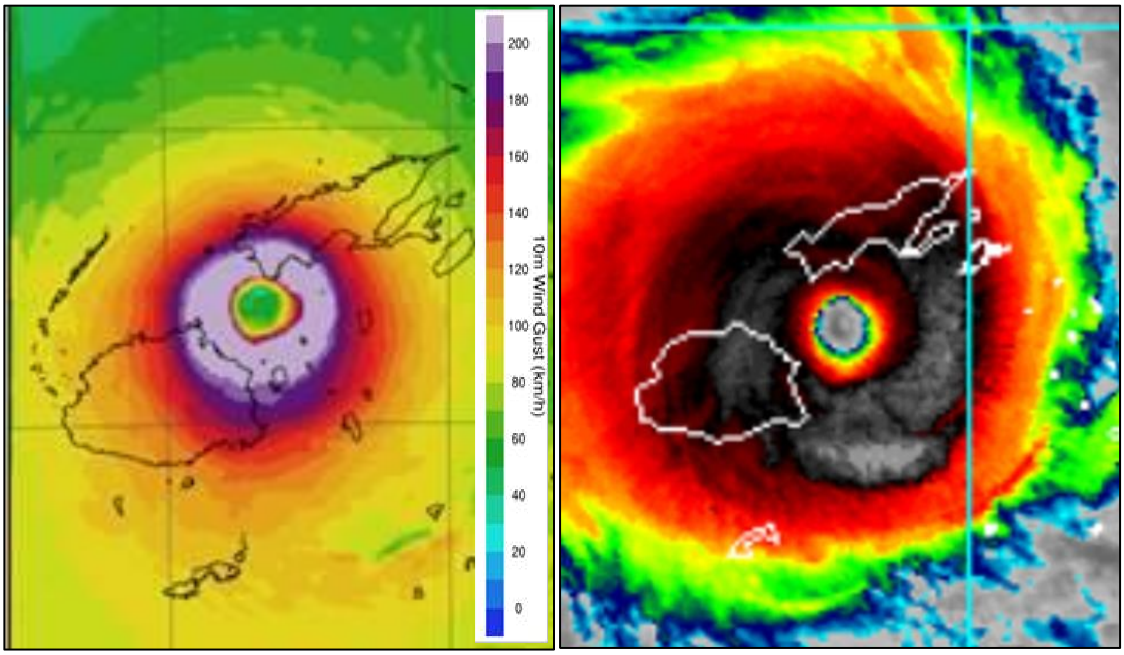

Figure 1. Comparison of TC Winston eye positioning and size valid at 0500 UTC on 20th February 2016. Left panel is the simulated 10m maximum wind gust speed from the 1.5 km UM and the right panel is Himawari 8 cloud top temperature imagery for the same time.

Qualitatively, the 1.5 km model has done a very good job of forecasting the storm location and size, even with a 31-hour lead time. From the same model forecast, modelled wind and pressure values were also compared against ground-based observations. Table 1 compares these for Vanua Balavu, Levuka, and Ba.

Table 1. Comparison of observed and modelled minimum surface pressures and 10 m 3-second gusts at Vanua Balavu, Levuka, and Ba on 20th February 2016. To account for forecast timing and track errors, the modelled estimates are for forecast hours within 2 hours of minimum central pressure being recorded at each site and for grid-cells located in a similar position relative to the eye.

	Observed		**Modelled**	
Site	**Min sfc pressure (hPa)**	**Max 10m 3s gust (ms^{-1})**	**Min sfc pressure (hPa)**	**Max 10m 3s gust (ms^{-1})**
Vanua Balavu	929.5	85.0	936	74
Levuka	954.9	67.0	960	64
Ba	956.7	52.7	940	70

From Table 1, it is clear the 1.5 km model is quantitatively capable of forecasting some of the key elements of TC Winston, albeit the peak observed gusts are generally underpredicted by the model and low pressure centre remains too high. Regardless, such a forecast is still a useful in corroborating aerial or ground-based photo assessments of storm damage where local observations are not available.

A horizontal resolution of 1.5 km is likely still too coarse to be able to resolve the topographic features of Fiji and its outlying islands which will have played a dominant role determining the near surface wind field. To counter this, additional forecast runs of the UM are made at horizontal resolutions approaching 100 m using underlying topography data at similar resolutions in an attempt to capture the local near surface wind field as well as possible. Forecasts from multiple initial times also, giving a lagged ensemble of forecasts to capture the forecast variability of the storm, are also completed. An ensemble of forecast wind speeds and central pressures enables confidence intervals to be generated that can be used downstream to assess both conservative and best-case damage scenarios. This work is ongoing.

4. Hill Shape and Terrain Category Modelling

A further benefit of running the NWP model to resolutions approaching 100 m, where the local terrain is more accurately resolved, is that estimates of the hill shape effects and terrain category, components regularly used in wind action calculations, can be directly modelled and compared against those calculated from the Standards themselves. When accompanied by the modelled wind fields, in particular the modelled surface wind gust, forecast estimates of point-of-damage wind speeds can be calculated for individual properties that have been surveyed post-event.

Using UM forecast output, these factors are being evaluated per the AS/NZS 1170.2 (2011) Standards on Wind Actions (Standards Australia, 2011) and will inform on both the validity of the Standards in terms of the wind speeds that should be expected over a given terrain or region and in validating the outcomes of loss/damage disaster analysis tools such as RiskScape. This work too is on-going and initial results will be presented.

5. Evaluating the loss and damage impact of TC Winston

Vulnerability models are one way of forecasting the likely impact, both on built infrastructure and economic loss, a given event will impart. For natural hazard events, NIWA, in conjunction with GNS Science, has developed the RiskScape impact and loss evaluation tool.

In quiet times, these models can be used to evaluate worst-case scenarios based on hypothetical events, advising on how new infrastructure projects could be developed to minimise against large losses. In post-event use, on-the-ground damage surveys, coupled with event observations and more recently high resolution NWP forecasts of surface winds, can be used as input to the vulnerability models so that damage functions for various building types and materials can be more rigorously tested and updated accordingly. Ultimately, we plan to apply an ensemble of NWP simulated wind (gust) fields for the TC Winston event to the wind hazard module in RiskScape so that damage functions and loss estimates can be forecast against the database of surveyed building assets in Fiji.

Preliminary investigations in this area, where we have extracted the forecast 10 m wind gust speeds for each surveyed building location where subjective estimates of the damage state (a scale from 0 (no damage) to 5 (complete destruction)) from a series of NWP forecasts at different horizontal resolutions, valid at the time TC Winston landfall near Rakiraki, located in the north-east corner of Fiji, yield the mean wind speeds (see Table 2) needed to reach a given damage state for timber and concrete masonry buildings.

Table 2. Tables showing the mean and standard deviation (in brackets) wind speeds required for timber and concrete masonry buildings to reach a given damage state based on simulated 10 wind gust speeds as forecast at the time TC Winston made landfall at Rakiraki.

Damage State	333m model resolution		1.5km model resolution		12km model resolution	
	Timber	Concrete	Timber	Concrete	Timber	Concrete
DS0	19.97 (0.29)	20.34 (2.36)	18.25 (0.25)	17.72 (1.88)	17.36 (0.54)	16.83 (0.93)
DS1	20.25 (1.49)	20.57 (1.53)	17.83 (1.42)	17.95 (1.24)	16.97 (0.58)	17.02 (0.49)
DS2	20.21 (1.53)	20.68 (1.28)	17.91 (0.64)	17.96 (0.67)	17.13 (0.31)	17.08 (0.22)
DS3	19.97 (2.25)	20.19 (2.14)	17.92 (1.90)	17.79 (1.78)	16.92 (0.86)	16.90 (0.82)
DS4	20.09 (2.20)	20.02 (1.55)	18.32 (1.50)	17.97 (0.74)	17.16 (0.36)	16.97 (0.14)
DS5	18.88 (3.06)	17.27 (2.72)	18.82 (2.12)	18.59 (0.71)	17.32 (0.52)	16.98 (1.36)

Typically, one would expect the (gust) wind speed required to reach increasing damage states would increase but Table 2 suggests this is not always the case here. This could be due to limits of survey size and possible under-representation of certain building types and/or damage states in the survey. Further, it is likely that the timber buildings were predominately single storey constructions compared to concrete buildings that were multi-storey. This would have affected their damage state and survivability also. This information was recorded in the survey and requires further analysis.

Nonetheless, from this analysis, we can begin to formulate fragility curves for the different construction types. Figure 2 shows derived fragility curves for timber and concrete masonry buildings for the damage state 1 (defined as insignificant damage).

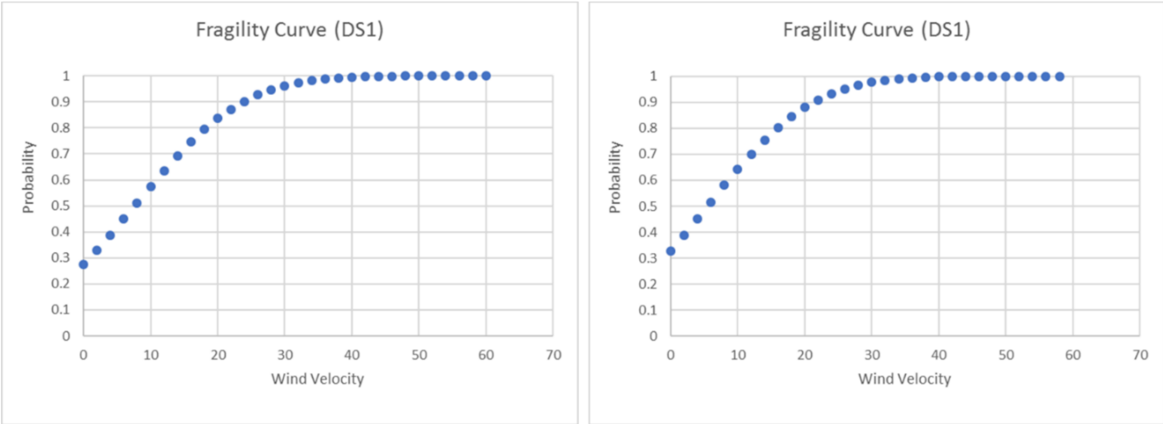

Figure 2. Example fragility curves for timber (left panel) and concrete masonry (right panel) buildings showing for a given wind speed, the probability of attaining damage state 1 (insignificant damage) based on the post TC Winston damage survey and NWP simulations of TC Winston at 3 different horizontal resolutions.

On-going work will see both observations and an ensemble of NWP forecasts with different forecast lead times and different horizontal resolutions relating to TC Winston used to further refine the derived fragility curves and act as input to RiskScape's wind hazard module to generate pre- and post-event damage estimates. This work will inform on future wind hazard module developments and ultimately lead to improved estimates of wind-induced damage being provided to a variety of stakeholders who have a vested interest, including regional civil defence authorities, governments and insurance companies.

6. Conclusions

Initial results from a 1.5km resolution NWP model used to simulate the passage of TC Winston over Fiji in late February 2016 have been shown. The model was able to well simulate the storm track and forecast surface pressures and wind gust speeds compared to observations. Output from these and planned future model simulations, including simulations at resolutions as high as 100 m with appropriately resolved terrain data, will be used in future work to estimate and compare against the terrain category and hill shape effects that inform the design wind estimates used in building design and in testing the accuracy and reliability of natural hazard disaster risk/loss tools such as RiskScape. Used in conjunction with results from post-event damage surveys and observations, we will show how high resolution NWP can aide the continued development of vulnerability models and damage functions for different types of built infrastructure which are needed for better planning and mitigation against events of this type.

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