AWES2020
20th Australasian Wind Engineering Society Workshop
8 – 9 April, 2021

Modelling Maximum Credible ex-Tropical Cyclone Events Over Auckland, New Zealand

Ian Boutle[1], Stuart Moore[2], Richard Turner[3]
[1]ian.boutle@metoffice.gov.uk 1.
[2]stuart.moore@niwa.co.nz 2.
[3]richard.turner@niwa.co.nz 3.

ABSTRACT

The north of New Zealand is impacted by around 1 ex-tropical cyclone per year. Luckily however, Auckland city has never experienced a direct “hit” from the severest of these storms. Thus, the potential economic and infrastructure impact on Auckland and New Zealand are not well understood. In order to try and quantify these impacts and better understand New Zealand’s resilience to these storms we have investigated questions such as "what if the path of recent historic and severe ex-Tropical Cyclones had directly passed over Auckland?” Here, we detail the novel modelling approaches to "shift" the NZ land mass around the model domain, so that the historic severe ex-tropical cyclones are modelled to hit Auckland. This has resulted in the creation of very high-resolution spatially and temporally consistent rain, wind, flood, and landslide scenarios, thus allowing for the development of detailed impact studies and credible worse-case scenarios for Auckland.

1. Introduction

High impact weather can have severe adverse impacts on many aspects on society and building an understanding of these is an important mitigation tool for use by many decision makers. One way to do this is through the use of high-resolution (i.e., detailed) scenario modelling. As part of New Zealand's National Science Challenges "Resilience to Nature's Challenges" research programme (https://resiliencechallenge.nz/scienceprogrammes/weather-theme/), a series of large-domain high resolution modelling simulations (at resolutions not accessible to most-impact model researchers) of past ex-tropical cyclone, wildfire and extreme winter storm events have been performed and made available to researchers to quantify the multi-component affects, covering wind, flood, snow, landslide, rural fire, etc., on infrastructure, buildings and communities.

Ex-tropical cyclones (ex-TCs) have historically been amongst the highest impact extreme weather events to affect New Zealand, e.g., ex-TC Ita in 2014 or ex-TC Giselle in 1968 (Revell and Gorman, 1998). On average one ex-tropical cyclone comes within 500 km of New Zealand each year and has some impact on the country although inter-year variability is high with intense years receiving three or four systems (Lorrey et al., 2014). The greater Auckland region is very important economically and has around 1/3 of the population New Zealand, but the city has never experienced a “direct” hit from the severest of these storms. Thus, the potential economic and infrastructure impact on Auckland and New Zealand are not well understood. New Zealand's latitude (34.4°S to 47.3°S) means that any Tropical Cyclones threatening the country will have undergone an extratropical transition as they move south. The transition is due to the increased wind-shear and colder sea-surface temperature (SST) in mid-latitude regions (Sinclair, 1993b) and typically results in broader and weaker systems and weaker surface winds. However, while weaker, heavy rainfall and damaging winds still occur and these have a range of socio-economic impacts including flooding and landslides with significant damage to power lines, buildings and vegetation (Lorrey et al., 2014). Coastal areas have the additional dangers presented by extreme storm surges and waves.

This presentation details our research into developing credible worse-case and high-impact weather events on Auckland. We do this with an illustrative example where the path of recent historic and severe ex-Tropical Cyclone Cook , which did much damage on the eastern Bay of Plenty coast in 2017 due to severe winds (the most extreme in the records for some locations) is modelled to be "dynamically shifted" west and hit Auckland. This approach "shifts" the NZ land mass around the model domain using the Unified Model (see Section 2) so that the storm track passes over or close to Auckland, but with the modelled storms allowed to "dynamically" evolve according to its position relative to the New Zealand land mass. By performing a series of these land mass "shifts" for a number of storms, an ensemble of scenarios are created allowing detailed impact modelling to be done for a variety of coincident weather, flood, and landslide hazards – building a credible worse-case impact scenario for Auckland and surrounding districts.

2. Modelling approach

2.1 Creating an ensemble of land-falling cyclone cases.

In the 1970-2010 climatology presented by Lorrey et al. (2014), only 5 ex-TCs have made landfall within 100 km of Auckland, with the closest being TC Norman in 1977, which made landfall 53 km south of the city on the western coastline. Whilst a reanalysis of these systems would undoubtedly be of value, our wish to investigate the potential "worst-case" scenario requires us to look outside of the recent historical record. One possible approach would be to modify or nudge the atmospheric state of existing systems in a way which diverts their track into more hazardous (from a human perspective) locations. However, this is likely to be very difficult to achieve in practice, due to the range of complex atmospheric interactions which determine a cyclone track (e.g. Sinclair, 1993a, 2004). Bruyere et al. (2019) detailed an approach for Australia in which an idealised TC is transplanted into a real-world scenario. Although appealing in its design, there are a number of challenges that would need to be overcome to implement this approach for New Zealand. Chiefly these are, that the increased track length and development time of a TC undergoing an extratropical transition would likely require expensive trial-and-error simulations to achieve landfall in the desired location and secondly the generation of an ensemble of different systems (different intensities, different approach tracks), would require starting the track generation process from scratch for each new scenario added.

Our methodology uses a simpler approach - we leave the atmosphere alone and move the location of a particular land mass within that environment. Selecting from storms which passed within a few hundred km of Auckland, and systematically repositioning the location of New Zealand such that Auckland falls near the historical path of that system, allows us to analyse what would have happened had that system made landfall at a particular location. Five recent systems, listed in Table 1, were selected. These systems were chosen because of their track location passing near enough to New Zealand to allow the above repositioning process to be applied, and their recent history ensuring that the analysis, and therefore control simulations, are as accurate as possible. Each repositioning is designed to give a landfall of each ex-TC in the vicinity of Auckland, but all cases are run for a range of land locations, giving an ensemble of 30 ex-TC events affecting New Zealand in different ways.

We use the second Regional Atmosphere and Land "Tropical" (RAL2-T) configuration of the Met Office Unified Model (UM, Bush et al., 2020). A limited area domain of 1100x1100 grid-points at 1.5 km spacing is nested inside the Global Atmosphere (GA) 6.1 configuration of the same model (Walters et al., 2017). Global simulations at 17 km grid-length are initialised from the operational analysis

Table 1: List of ex-tropical cyclone case studies.

Name	**Date**
Cook	12/04/2017
Donna	11/05/2017
Lusi	14/03/2014
Pam	14/03/2015
Victor	26/01/2016

generated by the UM's hybrid ensemble/4D-Var data assimilation scheme (Clayton et al., 2013), and in turn provide the initial and boundary conditions required by the high-resolution inner domain. The inner domain is convection permitting (i.e. it runs without a convection parametrization), and such models have been shown to considerably out-perform the global model in predictions of storm intensity, rainfall location and rapid intensification (Short and Petch, 2018).

For scenarios that were particularly impactful for Auckland even higher resolution (333 m grid-spaced) simulations were carried out. Sub-kilometer (or city-scale) numerical weather prediction (NWP) modelling has become commonplace in recent years (Boutle et al., 2016), due to its ability to provide unprecedented extra detail in atmospheric conditions above and within our most populated areas.

2.1 Benefits and weaknesses of the chosen methodology

The key advantage of the chosen methodology is that all meteorological fields within the simulation are self-consistent. That is to say that the position of the shifted land mass will feed back onto the cyclone evolution, in a way that will alter wind speeds and precipitation amounts consistent with a system making landfall. This dynamical consistency is crucial for driving downstream impact models, such as flood modelling or building wind-stress analysis. One could instead consider a naïve “postprocessing" methodology, where the observed (or simulated) fields of a real system were used to drive impact models at different spatial location (i.e. shifting the land mass onto pre-existing fields). This would however likely lead to over-estimation of the wind-strength (as this usually weakens on making landfall), but could also lead to under-estimation of precipitation amounts, which may be enhanced by local orography. This is illustrated further in Section 3 (Results).

There are several potential issues and uncertainties arising from artificially shifting a land mass. The most likely to be significant for tropical cyclone evolution is the SST, which is fixed (at analysis time) in our atmosphere-only set-up. Figure 1 shows the surface temperature after 24 hours of the TC Cook simulation. In order to retain realism we limited the land-shifts to longitudinal directions, thus preserving the location of New Zealand with respect to the background SST gradient. This also helps to preserve Coriolis effects, another key factor in cyclone evolution. However, features in the SST created by the presence of the land mass, such as the cold water to the east of the South Island and warm water to the east of the North Island, now appear displaced as this method retains the longitude and latitude positions of ocean currents and SST’s. As the main spin-up region north of New Zealand is unaffected, and we are mainly interested in the first landfall at the northern coastline we consider this to be of minor importance. Land surface properties are transplanted along with the land mass from their original location, and are free to evolve to their new environment, which can be observed in some surface temperature differences in Figure 1. This does create an issue with the blending of the orography between driving and driven models on the south boundary of the domain. Given this is considered as the outflow boundary for the simulation, we do not consider it to be a problem, but note that it would present a more significant issue if there was more land in the spin-up region or at the inflow boundary.

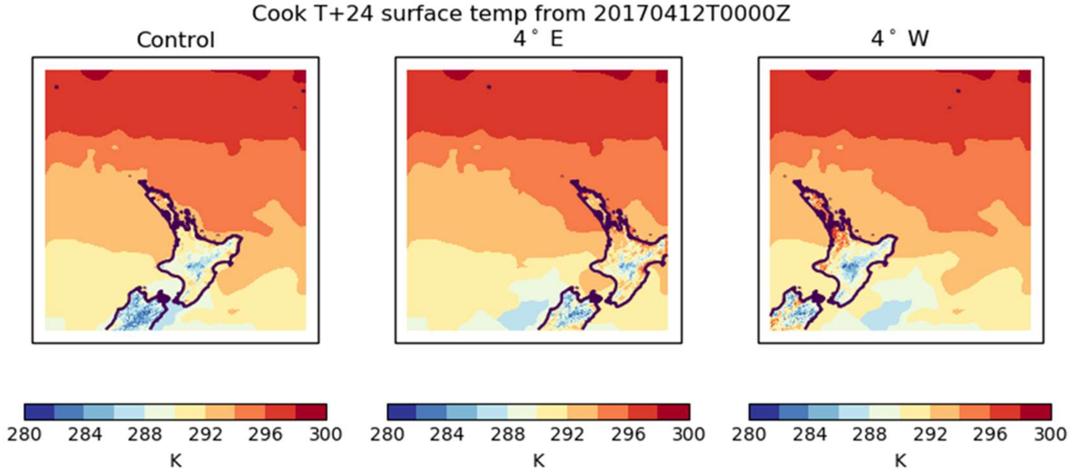

Figure 1: Surface temperature plotted on three of the selected shifts (shown in the panel titles) for TC Cook.

3. Results

In order to ascertain the benefits of the dynamical approach to impact modelling, in this section we will use examples from TC Cook to compare the methodology introduced in Section 2.1, termed "dynamic", with the simpler method discussed in Section 2.2, termed "post-proc". This will show what impacts are to be expected regardless of landfall location and what impacts are crucially dependent on precisely where landfall is made.

Figure 2 shows the maximum wind gust associated with the storm. This is strongly confined to the track of the storm (shown by the minimum sea-level pressure). Areas close to the track can experience wind-gusts in excess of 60 m/s (216 km/hr), with sustained wind-speeds exceeding 40 m/s (144 km/hr, not shown). In the control simulation, the wind-gusts have decayed slightly before the storm made landfall, but in the 2 deg E dynamic simulation, the wind-gusts remain high, and if anything, intensify slightly as the storm moves into the Hauraki Gulf and approaches Auckland. This is shown in more detail in Figure 3 where the 333 m simulation shows additional enhancement of gusts

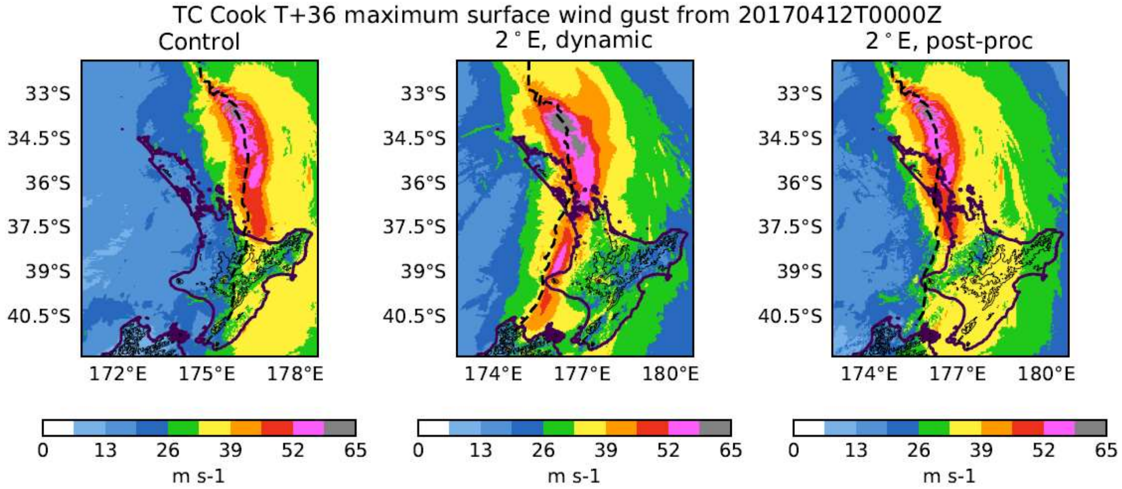

Figure 2: Maximum wind gust plotted for the control simulation of TC Cook (left), a 2 degree East dynamic shift of the land mass (middle) and a 2 degree E post-processed shift of the land mass (right). The dashed line shows the minimum sea-level pressure track.

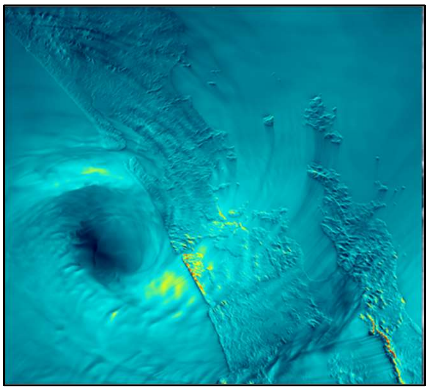

Figure 3: Unified Model Nested Weather Model (333 m horizontal grid spaced) simulated surface wind gust (brighter colours = stronger gusts – maximum simulated gusts of about 70 m/s red) at 3 pm April 13 2017 during the passage of ex-Tropical Cyclone Cook assuming a dynamic 2 degree eastward shift from the actual storm track.

along the coastline, and the potential for high gusts to be sustained much further inland. It also shows the sheltering effects within the harbour, and the increased gustiness along the westerly shore of the harbour, which is poorly represented at 1.5 km. The 333 m simulation also suggests that strongest gusts are somewhat unconnected with the local orography, with similar peak gust strengths received at similar distances inland regardless of terrain height. The primary effect of the orography appears to be in shading areas downstream of the terrain, which have much reduced gust strengths.

The location of the orography and surface temperature in this region all combine to keep the storm strong, as it moves on potentially the most destructive path possible into downtown Auckland. Wind gusts continue to exceed 60 m/s (216 km/hr) on making land fall, far in excess of the highest gust recorded in a historical case of 129.7 km/hr (Lorrey et al., 2014). Comparing the dynamic and post-proc results again shows the additional detail provided by the dynamic simulation. The post-proc results do not exhibit the sustained and intensified winds as the system moves into the Hauraki Gulf and the wind gust estimates are somewhat lower for the Auckland region (yet still very strong). The inability of the post-proc results to represent the decay of the system over land also results in an over-estimate of the gust strength for areas south and west of Auckland by around 15 m/s (54 km/hr).

Another interesting effect of the 2 deg E simulation (Fig 2) is that in passing directly over Auckland, it crosses the narrowest point of the country, and therefore loses the minimum intensity due to increased surface drag. All other simulations which contain a more sustained track over land decay much more significantly. The consequence of this is that the storm re-intensifies as it moves into the Tasman sea, and has recovered its strongest wind-gusts just in time to make a second landfall in the Taranaki/New Plymouth area. From a country-wide perspective, this is probably one of the most destructive cases possible, making landfall in two significant population centres. Further, the system was again able to redevelop a third time and make landfall near Nelson. This re-intensification is something which can only be represented with the dynamic simulation, with the post-proc results showing the track moving in broadly the same location, but with much reduced wind-gusts.

4. Conclusions

This paper has discussed a new methodology for studying the impacts of land-falling tropical cyclones. By making small adjustments to the geographic position of a land-mass of interest, within an otherwise fully self-consistent, high-resolution NWP model, the effect historical TC cases would have had with a slightly different track can be studied. To the authors knowledge, this technique has not been used before, despite its relative simplicity to implement. The closest existing study is that of Bruyere et al. (2019), who described a method to place an idealised tropical cyclone into a real-world scenario. Their method while appealing, adds considerable complexity in the initialization of the simulations and effort in generating an ensemble of scenarios similar. Our method is a complementary addition to the tropical cyclone impact modelling toolbox and we believe both methods provide significant advantages over traditional statistical methods.

We have documented the dataset which has been made available to impact modellers within New Zealand for downstream studies and illustrated what the model would predict for a strong ex-TC making landfall in central Auckland. The results show that planning and development in Auckland needs to consider wind gusts and rainfall totals in excess of those within the historical record if it is to mitigate against such a future scenario. We have demonstrated the level of detail contained within the baseline dataset, which due to the convection permitting grid-scale, is much greater than typically found in climate projections or statistical analysis methods. We have also shown the additional further detail which can be gained from sub-kilometer (or city scale) modelling.

References

Boutle, I. A., Finnenkoetter, A., Lock, A. P., and Wells, H., 2016. The London Model: forecasting fog at 333m resolution. *Q. J. R. Meteorol. Soc.*, 142, 360-371. 10.1002/qj.2656.

Bruyere, C. L., Done, J. M., Jaye, A. B., Holland, G. J., Buckley, B., Henderson, D. J., Leplastrier, M., and Chan, P., 2019., Physically-based landfalling tropical cyclone scenarios in support of risk assessment. *Weather and Climate Extremes*, 26, 100229. 10.1016/j.wace.2019.100229.

Bush, M., Allen, T., Bain, C., Boutle, I., Edwards, J., Finnenkoetter, A., Franklin, C., Hanley, K., Lean, H., Lock, A., Manners, J., Mittermaier, M., Morcrette, C., North, R., Petch, J., Short, C., Vosper, S., Walters, D., Webster, S., Weeks, M., Wilkinson, J., Wood, N., and Zerroukat, M., 2020. The first MetOffice Unified Model; JULES Regional Atmosphere and Land configuration, RAL1. *Geosci. Model Dev.*, 13, 1999-2029. 10.5194/gmd-13-1999-2020.

Clayton, A. M., Lorenc, A. C., and Barker, D. M., 2013. Operational implementation of a hybrid ensemble/4D-Var global data assimilation system at the Met Office. *Q. J. R. Meteorol. Soc.*, 139, 1445-1461. 10.1002/qj.2054.

Lorrey, A. M., Griffiths, G., Fauchereau, N., Diamond, H. J., Chappell, P. R., and Renwick, J., 2014. An ex-tropical cyclone climatology for Auckland, New Zealand. *Int. J. Climatol.*, 34, 1157; 1168. 10.1002/joc.3753.

Revell, M. J. and Gorman, R. M., 1998. The Wahine storm": Evaluation of a numerical forecast of a severe wind and wave event for the New Zealand coast. N*ew Zealand Journal of Marine and Freshwater Research*, 37, 251; 266. 10.1080/00288330.2003.9517163.

Short, C. J. and Petch, J., 2018. How Well Can the Met Office Unified Model Forecast Tropical Cyclones in the Western North Pacific, Weather and Forecasting, 33, 185{201. 10.1175/WAF-D-17-0069.1.

Sinclair, M. R., 1993a. A Diagnostic Study of the Extratropical Precipitation Resulting from Tropical Cyclone Bola. *Mon. Weather Rev.*, 121, 2690-2707. 10.1175/1520- 0493(1993)121<2690:ADSOTE>2.0.CO;2.

Sinclair, M. R., 1993b. Synoptic-Scale Diagnosis of the Extratropical Transition of a Southwest Pacific Tropical Cyclone. *Mon. Weather Rev.*, 121, 941-960. 10.1175/1520-0493(1993)121<0941:SSDOTE>2.0.CO;2.

Sinclair, M. R., 2002. Extratropical Transition of Southwest Pacific Tropical Cyclones. Part I: Climatology and Mean Structure Changes. *Mon. Weather Rev.*, 130, 590-609. 10.1175/1520-0493(2002)130<0590:ETOSPT>2.0.CO;2.

Sinclair, M. R., 2004. Extratropical Transition of Southwest Pacific Tropical Cyclones. Part II: Midlatitude Circulation Characteristics. *Mon. Weather Rev.*, 132, 2145{2168. 10.1175/1520-0493(2004)132<2145:ETOSPT>2.0.CO;2.

Walters, D., Boutle, I., Brooks, M., Melvin, T., Stratton, R., Vosper, S., Wells, H., Williams, K., Wood, N., Allen, T., Bushell, A., Copsey, D., Earnshaw, P., Edwards, J., Gross, M., Hardiman, S., Harris, C., Heming, J., Klingaman, N., Levine, R., Manners, J., Martin, G., Milton, S., Mittermaier, M., Morcrette, C., Riddick, T., Roberts, M., Sanchez, C., Selwood, P., Stirling, A., Smith, C., Suri, D., Tennant, W., Vidale, P. L., Wilkinson, J., Willett, M., Woolnough, S., and Xavier, P., 2017. The Met Office Unified Model Global Atmosphere 6.0/6.1 and JULES Global Land 6.0/6.1 configurations. Geosci. Model Dev., 10, 1487-1520. 10.5194/gmd-10-1487-2017.