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Tropical Cyclone Yasi: a lucky escape? A counterfactual storm surge ensemble analysis

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Abstract

Tropical Cyclone (TC) Yasi impacted Australia in 2011 with damaging winds and coastal flooding. Its exact landfall location and timing acted to limit the damage caused by its storm surge, making landfall in a sparsely-populated area at low tide. Here, we perform a systematic counterfactual analysis to evaluate a large range of plausible alternative outcomes for a Yasi-like TC, and compare these to the realised Yasi. We perturb the landfall location, timing and track bearing, and evaluate the resulting change in storm surge water levels, inundated depth and area, population impacted, and property damages due to surge only using a 2D hydrodynamic modelling system coupled to a catastrophe modelling framework. We conclude that Yasi was very much a “near miss”, with the actual event being within the 20% smallest realisations within our counterfactual ensemble in terms of hazard and well below the median of possible damage outcomes. The alternative scenarios highlighted the potential to affect a population and produce losses ten times greater, had Yasi occurred at the same location but at higher tidal conditions. Impacts would have been significantly larger than this had it made landfall at other locations within the pre-landfall forecast cones of uncertainty such as Cairns or Townsville, with maximum losses increasing by another order of magnitude. These findings serve to underline the very real risk of damaging TC-driven storm surge which exists in Queensland.

Keywords: storm surge, counterfactual analysis, tropical cyclone, coastal flooding, catastrophe modelling

1 Introduction

Australia frequently experiences Tropical Cyclones (TCs), with the region seeing on average 9–11 TCs per year, and 4–5 typically making landfall[1]. Recent years have seen major damage caused by TCs such as Debbie (2017), Marcia (2015) and Yasi (2011), with total insured losses for these events ranging between AUD 800 million and AUD 2.3 billion (normalised to 2022 AUD)[2]. Most of this damage, however, has come from strong winds and precipitation rather than from storm surge, as discussed next.

Coastal flooding driven by TCs can be amongst the most costly and lethal natural disasters on Earth[3]. Not all TCs cause damaging storm surges, and the magnitude of a TC's storm surge is dictated not only by the strength and size of its wind field, but also by local factors such as the nearshore bathymetry, the tidal phase at the time of landfall, and the storm track prior to landfall. Surge heights are therefore complex to predict, as small changes to a storm track or arrival time can make a large difference to the resulting flooding.

In its modern history, Australia has not seen any catastrophically damaging TC storm surge events, despite its long coastline and high TC risk[4]. This is due to a number of known factors, in addition to the fundamental randomness of extreme event occurrence. Crucially, the sparsity of human settlements on its tropical coastline means that most TCs are unlikely to cause significant damage to property, and peak surge heights are not always even known. For example, recent powerful TCs such as Monica (2006), Ingrid (2005) and Rosita (2000) likely generated several-metres high storm surges at the coast, yet caused negligible economic damage due to their relatively remote landfall locations[5–7]¹. Despite the limited quantitative information available for earlier events, they nevertheless demonstrate the potential for catastrophic storm-surge impacts along the Queensland coast: Severe TC Mahina (1899) at Bathurst Bay and the 1918 Mackay and Innisfail cyclones all generated large storm surges, with the latter crossing the coast close to Yasi's landfall location 93 years later.

Tides can play a major role in modulating the risk from storm surge. A large tidal range acts as a natural defence by reducing the time window during which a TC can cause damaging flooding. If a tidal range is large compared with a TC's storm surge at a given location, then the combined tides plus surge water level (storm tide) will only exceed the high tide level if the peak storm surge occurs close to the timing of high tide. In addition, non-linear surge-tide interactions are known to increase the likelihood of the peak surge occurring away from the time of peak tide[8]. Much of the TC-prone coast in Australia has a significant tidal range, and this has served to avoid damage for a number of TCs which made landfall during low or moderate tidal phases, turning them from potential catastrophes into “near misses”, for example Debbie (2017), Yasi (2011), Larry (2006) or Althea (1974).

TC Yasi was the most recent damaging TC storm surge event to affect Queensland, making landfall near Mission Beach (and Cardwell) as a very large and intense Category 4 Cyclone (Saffir-Simpson) on 3rd February 2011[9]. Landfall occurred between the major settlements of Cairns to the North and Townsville to the South (Fig 1),

¹Given the damage to sand dunes and coastal vegetation recorded during these storms, they had the potential to be catastrophic if they had made landfall over heavily populated areas.

75 avoiding significant damage to either city, and during low tide. Official forecasts issued
 76 by the Australian Bureau of Meteorology (BoM) in preceding days had the storm
 77 making landfall well to the north and south of this location, with the cones of forecast
 78 uncertainty extending some 600 km, from Lizard Island in the North down to Cape
 79 Upstart in the South (Fig 1).

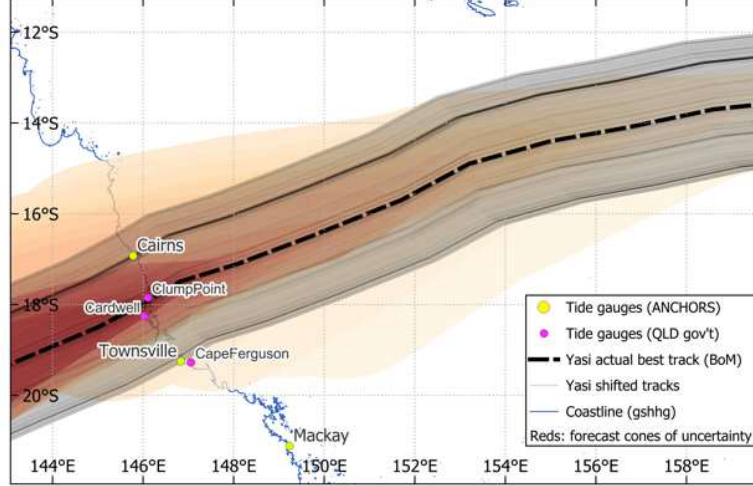


Fig. 1 Geographical domain. Actual TC Yasi track from BoM shown in black, longshore-shifted counterfactual tracks shown in grey, and cones of uncertainty of all BoM forecasts issued prior to the storm's landfall shown in shaded reds, to illustrate the large geographical uncertainty in landfall forecast positions. Locations of tide gauges are shown in yellow (long term ANCHORS gauges) and pink (shorter-term, QLD government-operated gauges).

80 The uncertainty in forecasts highlights that the reality observed is but one reali-
 81 sation of how things could have gone. To properly quantify the true, present-day risk
 82 from storm surges, we need to consider not only the likelihood that events similar to
 83 observed events could occur again, but also the possibility that as-yet unseen events
 84 may occur, with a probability which is as-yet unknown. A common way of doing this
 85 is to generate a synthetic catalogue encompassing the full range of physically plau-
 86 sible TCs in a given region – a stochastic event set – and evaluate their impact in
 87 terms of physical damage and economic loss. This is defined as a *catastrophe model*,
 88 and such models are frequently used within the insurance industry to understand and
 89 price natural catastrophe risk[10, 11].

90 In addition, counterfactual disaster analysis (CFDA) is a risk assessment approach
 91 based on evaluating realised historical disasters, and considering their damage-causing
 92 potential if they had occurred slightly differently to reality. In other words, it aims
 93 to evaluate their unrealised damage potential, within a plausible parameter space
 94 range[12, 13]. CFDA is a useful tool in allowing us to broaden our understanding of
 95 realised extreme weather events, plan for plausible future events, and also to validate
 96 stochastic ensemble event sets of *catastrophe models* (e.g. see Rye and Boyd[14]).

In this study, we conduct a rigorous “what-if” CFDA of TC Yasi to assess the coastal flood damage that might plausibly have occurred under slightly different circumstances. We construct an ensemble by perturbing three aspects of the observed storm: its timing relative to the tide, the precise location of its track along the Cairns–Townsville coast, and the angle at which the track approached the coastline. Within the limited ranges considered, these aspects could plausibly have differed from those observed, producing outcomes that may have been roughly as likely as the realised event. Our aim is not to generate a stochastic set of all possible Australian TCs (see, for example, Arthur[4] and Haigh et al.[15, 16]). Instead, we take the occurrence of a Yasi-like event in the present climate as given and examine its sensitivity to these particular perturbations. Other storm characteristics, notably intensity and size, can also strongly affect surge, but we do not vary them because they are more closely linked to climatological conditions, which lie outside the scope of this analysis. For example, Lavender et al.[17] examined the sensitivity of Yasi’s surge to such conditions, particularly sea surface temperature (SST), and found that higher SSTs would likely increase damage. The present study complements that work by examining plausible variations in the storm’s timing and track.

We simulate the storm surge and storm tide for the real Yasi and the counterfactual ensemble using a calibrated, depth-integrated, unstructured mesh coastal ocean model, then simulate the resulting overland inundation using a high-resolution overland inundation model based on the shallow water equations. We calculate damage metrics for each scenario (population and buildings affected), as well as total economic losses to property from storm tide only using a catastrophe modelling framework, and evaluate the full range of possible losses from all counterfactual events. Our results are split into 3 parts:

- 1) The effect of landfall timing (i.e., tidal phase)
- 2) The effect of landfall location
- 3) The effect of track bearing at landfall

These analyses are ultimately combined to evaluate the worst-case combination at Cairns and Townsville in terms of water levels, inundation footprints and losses. Finally, we put in perspective the probability of Yasi’s effects in terms of the set of counterfactual scenarios.

2 Methods

2.1 Storm track and wind field

Yasi’s storm track is obtained from the Australian Bureau of Meteorology’s (BoM) Australian Tropical Cyclone Database[18]. This dataset contains 6-hourly TC centre location alongside storm parameters. These were used to construct Yasi’s wind field on a 2D grid, at 6-hourly snapshots, using the Generalised Asymmetric Holland Model (GAHM)[19, 20], a parametric TC vortex model. GAHM is based on the widely-used wind profile of Holland[21], but additionally accounts for asymmetry by incorporating azimuthally-varying (by quadrant) radius of maximum winds (information which is available from the BoM Yasi track), and does not assume cyclostrophic balance. Using

the GAHM-based wind field resulted in a better fit of modelled storm surge versus the classic Holland wind model.

2.2 Counterfactual Yasi scenarios

A range of different counterfactual Yasi tracks were obtained by perturbing certain parameters from the actual Yasi track:

- 1) The **timing of the landfall** was perturbed, in 15-minute increments, for up to 14 days either side of the actual landfall time, to account for the case that Yasi made landfall at a different tidal phase. These cases should be considered equally likely, as the timing of the landfall relative to the tidal phase is random (“any storm surge can occur on any tide” [22]). 28 days was judged to be a sufficient range, as it spans approximately two spring-neap cycles, which together with the semi-diurnal and diurnal tidal components, make up the majority of the tidal variability in the region. An additional analysis on Yasi’s tide levels against the 18.6-year tidal nodal cycle is provided in Appendix A. This step created $28 \text{ (days)} \times 24 \text{ (hours)} \times 4 \text{ (events per hour)} = 2,688$ counterfactual, timing-perturbed Yasi tracks.
- 2) The **location of the landfall** was perturbed, by shifting the track to a range of ± 175 km north/south of the actual landfall location, in 2 km increments along the coastline. This step resulted in the creation of 204 counterfactual, location-shifted tracks. The track orientation was unaltered for this perturbation; only the landfall location was modified, by shifting the track along the longshore axis. This range was judged sufficient to model the effects of a track making landfall along the stretch of coastline including the major settlements of Cairns and Townsville, whilst still being well within the range of plausible landfall locations as per the range of BoM forecast cones of uncertainty (Fig 1). For example, the first BoM forecast for Yasi’s landfall (issued 31st January 2011 at 11PM AEST) had a range of uncertainty of ± 270 km for Yasi’s landfall location.
- 3) The **bearing of the track at landfall** was perturbed, in 22.5° increments, from $+45^\circ$ to -45° . This was to simulate the arrival of a Yasi-like storm from a different angle relative to the position of the coastline. This resulted in the creation of four additional sets of bearing-modified tracks (five including the original).

Simulating all combinations of the three perturbations with the hydrodynamic model ($2,688 \text{ landfall times} \times 204 \text{ landfall locations} \times 5 \text{ bearing angles}$, corresponding to approximately 2.74 million tracks) was computationally infeasible. The perturbations were therefore combined sequentially in three stages, mirroring the structure of the Results section:

- 1) **Timing** (Section 3.1): the actual Yasi track was simulated in the hydrodynamic model with tidal forcing for each of the 2,688 landfall times, fully resolving the nonlinear tide and surge interactions, and with the inundation model to calculate impacts and losses.
- 2) **Location and timing** (Section 3.2): the 204 location-shifted tracks were first simulated without tides, yielding storm surge. At Cairns and at Townsville, the track producing the largest storm surge was then rerun in the hydrodynamic

model with tidal forcing for all 2,688 landfall times and with the inundation model to compute impacts and losses.

- 3) **Location, bearing and timing** (Section 3.3): each location-shifted track was rotated to the four alternative bearings, producing 816 additional tracks that were simulated in the hydrodynamic model without tidal forcing. For Cairns and Townsville, the highest-surge track associated with each of the three most surge-producing bearings was subsequently rerun in the hydrodynamic model with tidal forcing across all 2,688 landfall times. The resulting sets were used to train one linear surrogate model of peak storm tide per city (Appendix B), enabling peak storm tide to be estimated for all 2.74 million location–bearing–timing combinations at Cairns and Townsville. Finally, 110 scenarios spanning the range of predicted storm tides above HAT, comprising 11 scenarios for each bearing angle and city, were selected and rerun with the hydrodynamic and inundation models to quantify impacts and losses.

2.3 Coastal ocean hydrodynamics and overland inundation modelling

The storm tracks are used to force MIKE 21 HD FM (hydrodynamic flow model) developed by DHI, a 2D, unstructured grid, finite volume ocean model, whose domain runs from roughly 1,000 km offshore up to the coastline, and spanning the Coral Sea from Papua New Guinea in the North to Port Macquarie (New South Wales), in the South. The mesh was generated using the *seamsh* Python-based API[23] which is based on the gmsh mesh-generation tool[24], and model resolution was set to 2 km close to the coast at locations of interest such as towns and cities, rising to 40 km in open-sea areas. Bathymetric data used was Geoscience Australia’s AusBathyTopo (Great Barrier Reef) 30-metre-resolution dataset[25]. Tide gauge data for model calibration was obtained from the ANCHORS dataset[26] at Cairns and Townsville, and the Queensland Government tide monitoring sites at Cardwell, Clump Point and Cape Ferguson (Fig 1). Bottom roughness was parameterised using a Manning’s n approach, with $n=0.029$ over the sea floor, except over reefs where it was increased to $n=0.33$, following a detailed calibration of tidal amplitude and phase using tide gauge data. To simulate storm surge caused by TC Yasi (and its counterfactuals), the model was forced by wind stress applied at the water surface throughout the domain, with the wind field described earlier in this section, and at the boundaries using tidal boundary conditions extracted from the Technical University of Denmark’s DTU10 Global Ocean Tidal model[27], as implemented into the DHI MIKE software package. This hydrodynamic model was run for every counterfactual Yasi track, to generate a modelled storm tide or storm surge elevation (depending on the case) at the coastline.

The MIKE 21 HD FM model was one-way coupled with a 2D overland inundation model built in-house, at approximately 1 km from the coastline. The model solves the shallow water equations (SWEs) on a structured grid using a first-order upwind finite volume method. Fluxes are calculated with HLLC (Harten, Lax and van Leer) approximate Riemann solver[28], which can handle discontinuities (i.e., wet/dry interfaces, hydraulic jumps, and bores). In addition, an explicit-implicit method is implemented for temporal discretization with operator splitting (i.e., a forward Euler

for flux and bed slope and a backward Euler for friction slope) to prevent instabilities at the wet/dry interfaces[29]. A well-balanced method is also introduced to preserve non-negative water depths and ensure “lake at rest” property (C-property), following Audusse et al.[30].

Land elevation was obtained from two sources: in urban areas a 5-meter Digital Terrain Model (DTM) from Geoscience Australia (GA)[31], which was itself derived from some 242 individual project area LiDAR surveys between approximately 2001 and 2015 covering an area in excess of 372,000 square kilometres, while in other areas Copernicus DTM (COP-DEM, latest update in 2023) at 30 metre resolution[32] was used. Because remote-sensing products such as the Copernicus DEM (Digital Elevation Model) retain residues of buildings and vegetation, Moody’s improved this dataset using an in-house machine-learning (deep-learning neural-network) methodology to remove these artefacts and better represent bare-earth ground elevation. Bottom roughness in this model was parameterised using a Manning’s n formulation, with the value of n derived from Land Use/Land Cover categories (data from ESA WorldCover 2021 v200, 10 metre resolution[33]) mapped to values of n using an internal land-cover-to-roughness lookup methodology based on HEC-RAS documentation recommended values[34]. The SWE model was run at a native resolution of 38 metres, and model results were then downscaled to 19 metres by subtracting the value of the DTM (at 19 metres) from the modelled surface elevation (at 38 metres) to end up with a modelled water depth above ground at 19 metre resolution. This inundation model was run over a stretch of the coast from Cairns to Townsville, to end up with a modelled water depth footprint for each of the selected counterfactual Yasi tracks.

Coastal defences may not be explicitly captured in the DEM but are incorporated into this work as a mask that accounts for their presence and reduces flood impacts. The main assumption is that urban areas should at least be protected against the Highest Astronomical Tide (HAT). Consequently, local water depths are compared cell by cell against those from an inundation footprint produced by HAT conditions, and kept only if they surpass this threshold.

2.4 Physical damage and loss estimation

To estimate the population affected by each track, we overlaid the flooding footprint with the global building database of Zhu et al.[35], which provides building polygons, and the High Resolution Settlement Layer (HRS�) of Facebook Connectivity Lab and CIESIN[36], distributed as the Australia high resolution population density maps, which provides a population count raster at approximately 30 m resolution. For simplicity, and to reconcile the different vintages of the datasets, we assumed that the population of a given building is concentrated at its centroid and corresponds to the value sampled from the population raster at that point. Based on this methodology, the area simulated from Cairns to Townsville contains 260,255 buildings, 55% of which are occupied. There is an average of 2.4 persons per occupied building, leading to a total population in the area of interest of 341,425.

Additionally, economic losses were estimated following the approach described by Narayan et al.[37] and RMS[38]; we processed the Yasi counterfactual inundation footprints (for the region covering from 85 km north of Cairns to 80 km south of

Townsville) with a catastrophe model of the type commonly used within the insurance industry to price risk – the Moody’s Australia Cyclone HD Coastal Flood model. The model features a financial engine that ingests hazard (i.e., local water depth footprints) and combines it with exposure (property data) and vulnerability (how much damage is caused by a physical hazard); these are now described in turn.

Exposure is available in the model as the 2026 Moody’s Australia Cyclone HD Economic Exposure Database (EED), a commercial database of property exposure which includes property locations and rich characteristics describing all insurable residential and commercial properties in Australia, excluding public infrastructure. Therefore, the EED serves as a macro-level representation of all insurable assets across Australia, acting as a standard yardstick of the market. We remark that the EED represents a snapshot of present-day exposure and may not necessarily capture the actual exposure at the time TC Yasi occurred. As a result, the economic losses presented in this work should be interpreted as “if Yasi had happened today.”

Vulnerability consists of a series of region-specific damage curves that provide the damage ratio distribution for each asset type based on its features (e.g., construction type, occupancy, height or year built) and local water depth. Damage curves are derived from observations of flood damage compiled and developed by Moody’s, calibrated with proprietary data on historic flood insurance claims and structure types, including both physical damage and time element losses such as business interruption; following the same approach used in [37]. The model captures damage uncertainty by sampling from both a distribution of damage ratios and the possible locations of damaged buildings. Therefore, we ran the model 10 times per scenario to account for this second effect, and losses reported in the next section correspond to the average loss in 2026 AUD across all runs.

3 Results

3.1 Perturbing the landfall timing

We computed storm tide (ST) for the original Yasi track parameters and landfall location, varying the landfall time at 15-minute intervals for 14 days before and after the actual Yasi landfall near Mission Beach, between 0:00 and 1:00AM (AEST) on 3rd February 2011. These simulations capture the nonlinear interactions of the storm surge peak with the full range of astronomical tide levels for this period. For a full discussion on the astronomical tide regimes and highest astronomical tide (HAT) levels at Cairns, Cardwell and Townsville, the reader is referred to Appendix A.

The results shown in Fig. 2 indicate that all simulations yield an ST above HAT at Cardwell, highlighting that this event would have yielded significant overland inundation locally regardless of its landfall time. The observed and modelled ST values for the actual Yasi are within a 2 cm range (4.15 m and 4.17 m, respectively). These values are well below the median (4.78 m) and maximum (6.40 m) of the distribution for the period modelled, which indicates a high potential for a much more devastating event at Cardwell. This is also reflected in panel (c), which shows the cumulative distribution function of all STs. The likelihood of a more severe event in Cardwell is

81.8% if the landfall time is picked at random from the 28-day range, based on the percentile of the modelled Yasi being 18.2%.

Comparing modelled with observed ST for the actual Yasi, we find very good agreement close to landfall at the Cardwell gauge, whereas the fit is more noisy towards the edge of the affected coastline where the ST is much lower at Clump point (not shown) and Townsville (Fig. 2, panel a). As a result, observations at Clump Point and Townsville were both above HAT whereas modelled ST was below, with differences of 62 cm and 42 cm respectively. Nevertheless, the model shows potential to produce values above HAT at both locations depending on the tidal phase, see Fig. 2 panel (c), with 43.9% of the cases being above HAT at Clump Point (not shown) and 14.7% in Townsville. The observation and modelled values are closer in Cairns (within 21 cm), although the observation lies outside of the envelope of modelled STs. In any case, all values in Cairns, modelled and observed, are below HAT. This is consistent with the fact that Cairns is located to the less damaging right-hand-side of the landfall point relative to the forward trajectory of the cyclone.

Each of the 2,688 counterfactual cases – with the landfall timing shifted by 15 minutes, up to 14 days either side of the actual landfall time – was subsequently run to compute overland inundation with storm tide and wind as forcings, resulting in a set of 2,688 counterfactual inundation footprints. Each of these equally-likely scenarios was analysed in terms of the number of buildings, population affected (i.e., inundated to any depth) and economic loss, as already described.

Fig. 3 contains the analysis of the inundation impact in terms of buildings and population affected. Panel (a) shows the cyclical correlation of maximum ST from each simulation at Cardwell and Townsville, the two tidal gauges at which storm tide exceeded HAT, along with the number of impacted buildings, colour coded. The simple contours were calculated using Support Vector Machine (SVM), as the lines that best separate the points above and below the given thresholds. This representation has the advantage of providing the relative influence of each variable based on the normal vector to the line. For instance, 0° (vertical line, horizontal normal vector) means full Cardwell dependency, 90° (horizontal line, vertical normal vector) means full Townsville dependency, and 45° means equal contribution.

Although a positive correlation between ST and buildings affected is evident, the storm tide level at Townsville drives the increase when fewer buildings are affected (500 buildings contour, 49°). By the 750 and 1,000 contours (25° and 23°), storm tide at Cardwell largely dominates instead. The trend progressively reverses with the normals of the contours 2,000, 3,000 and 4,000 oriented at 38° , 47° , and 54° , respectively, coinciding with the highest ST values at both locations, which are mostly above HAT in Townsville too. This also reflects the fact that Townsville has a significantly higher population than Cardwell, so small increases in inundation depth have a proportionally greater impact on the population affected. Panel (b) provides the probabilistic view on the buildings and population affected. Since water levels at Cardwell are above HAT, the number of affected buildings starts at 326 and population at 191. Both magnitudes increase quite slowly, indicating that most of the cases produce similar effects, until above the 80th percentile, when the numbers start to grow rapidly up to a maximum of 4,537 buildings and 5,046 people. The simulation for the actual landfall time leads

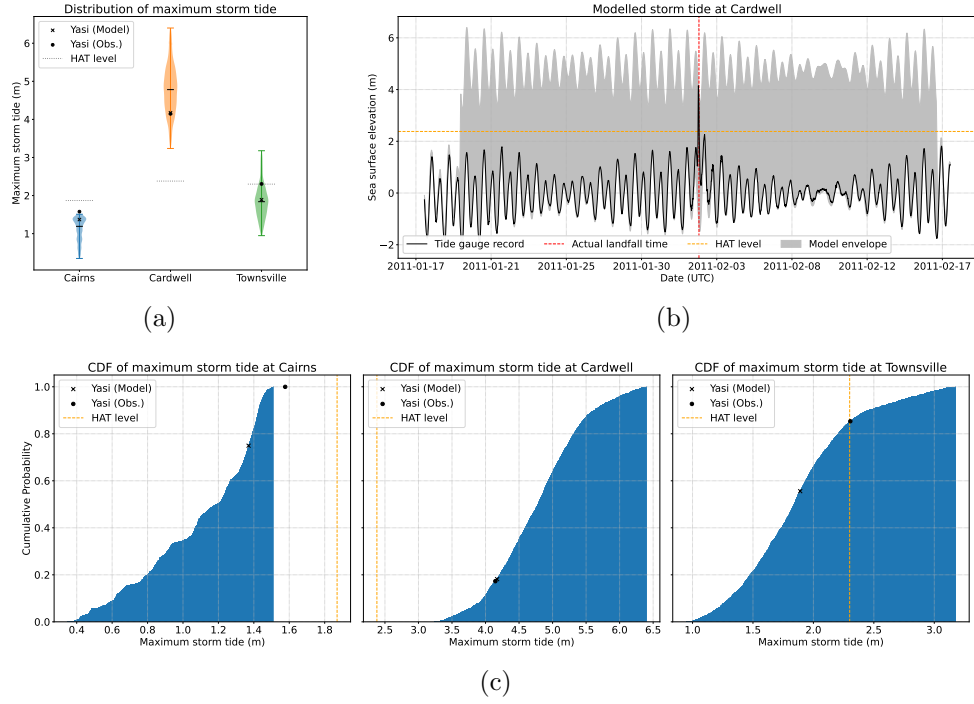


Fig. 2 Analysis on storm tide for different Yasi landfall times. (a) Distribution and validation of maximum storm tide at the relevant tide gauges. (b) Envelope of modelled storm tide at Cardwell. (c) Cumulative distribution function (CDF) of storm tide at the relevant tide gauges.

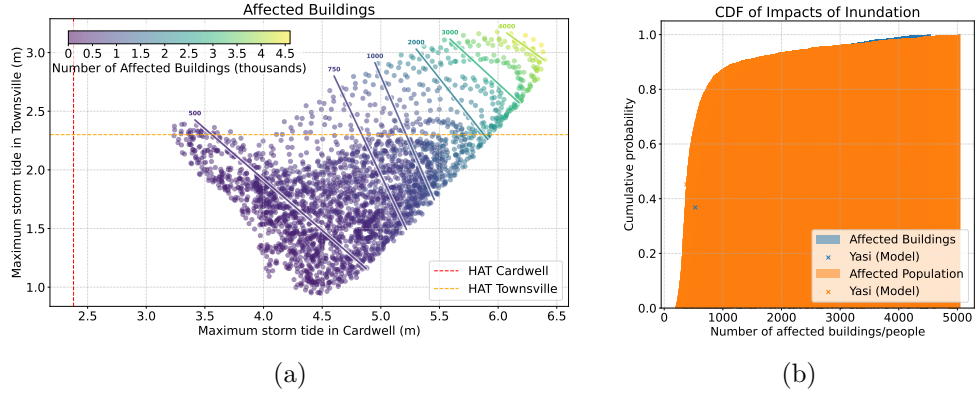


Fig. 3 Analysis of the overland inundation impacts for different Yasi landfall times for the actual Yasi landfall location. (a) Number of buildings counterfactual as a function of storm tide in Cardwell and Townsville (each point represents a different counterfactual perturbed-timing scenario). (b) Cumulative distribution function (CDF) of buildings and population affected by the 2,688 scenarios.

357 to 531 buildings and 378 population affected, which correspond to percentiles 36.8 and
 358 45.3, respectively.

359 There are 2 main takeaways:

- 360 • First, Yasi was a near-miss with a potential, solely based on landfall time, to
 361 affect 8.5 times more buildings and 13.3 times more population around the area
 362 where it made landfall.
- 363 • Second, the effects' percentiles are far above the percentile of maximum ST at
 364 Cardwell (18.2%). This means that the storm tide level at Cardwell has a limited
 365 influence on these results, since the largest values are driven by storm tide level
 366 in Townsville instead, as discussed before.

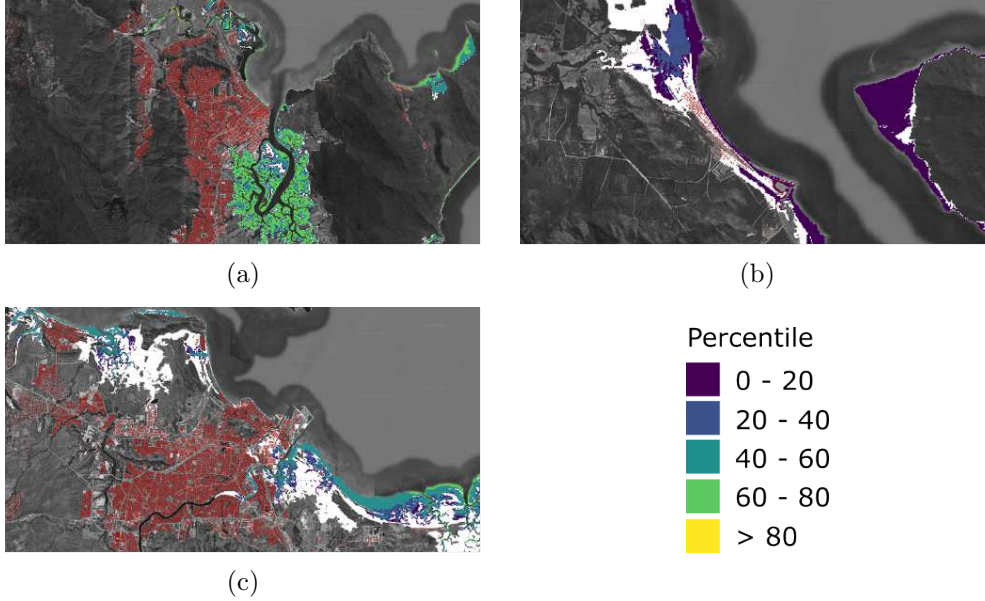


Fig. 4 Maximal inundation extent (white) and percentiles in terms of inundation depth of the actual Yasi event footprint (colorbar) with building footprints overlaid in red. Cairns in panel (a), Cardwell in panel (b) and Townsville in panel (c).

367 Fig. 4 presents the inundation extent of the Yasi reconstruction, coloured in terms
 368 of the percentile of local water depth calculated by grid cell, from among the complete
 369 set of 2,688 inundation simulations. The white areas indicate the maximal inundation
 370 extent among all the simulations and the red polygons overlaid represent the building
 371 footprints. Panel (a) shows Cairns, where Yasi's inundation depths are above the 60th
 372 percentile in many grid cells. However, the number of buildings affected is minimal,
 373 as Yasi's inundated area covers low-lying marshes or vegetated wetlands only and the
 374 maximal inundation does not extend into the urban area. Yasi's inundation extent in
 375 Cardwell (panel b) is limited to the coastline and depths are below the 20th percentile
 376 but still affects some buildings. This means there is a significant potential for a larger
 377 inundation extent, affecting many coastal properties several blocks inland. The situa-
 378 tion in Townsville is similar to Cairns in terms of the impact of Yasi being relatively

small. In contrast, the potential inundation covers a significant portion of the urban area, affecting numerous buildings. In general, the inundation results in Fig. 4 are in accordance with Fig. 2 (c), with the actual Yasi storm tide levels significantly below HAT in Cairns, above HAT but on the lower end in Cardwell, and below HAT but with potential to surpass it in Townsville. This highlights the fact that peak inundation extent overland is heavily correlated with the maximum storm tide level.

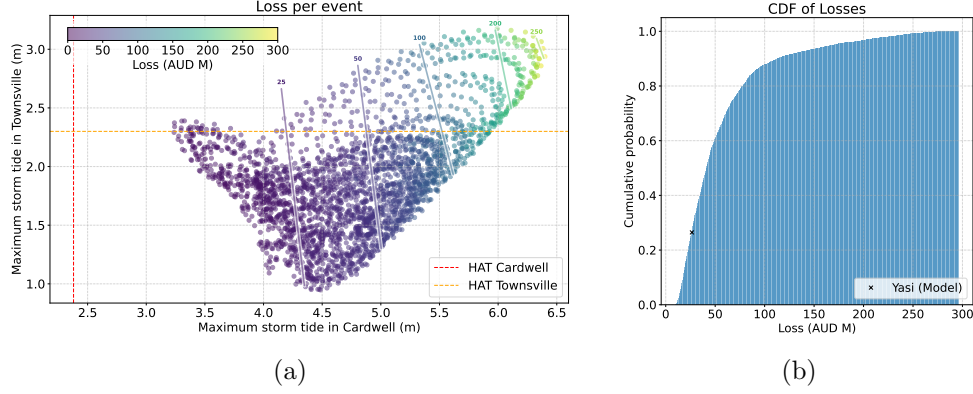


Fig. 5 Total economic losses for different Yasi landfall times for the actual Yasi landfall location. (a) Loss per event as a function of storm tide in Cardwell and Townsville. (b) Cumulative distribution function (CDF) of losses.

The loss results are presented in Fig. 5. Panel (a) shows the correlation between losses and the maximum storm tide at Cardwell and Townsville. The behaviour is visually analogous to the one in Fig. 3, indicating a high correlation between the number of buildings affected and losses ($R^2 = 0.93$), as can be expected. However, differences (i.e., scatter) can be expected for several reasons: the data sources and vintage of the building database and the EED are not the same, and losses depend on multiple factors (asset value, type and local water depth). The main difference between both figures concerns the orientation of the contour lines. In this case, losses are mainly driven by maximum ST in Cardwell, since the angle starts at 7° (AUD 25 million contour) and reaches 20° at the AUD 250 million contour. This indicates that the significantly larger ST in Cardwell leads to higher damage ratios, and thus, to higher losses overall. Panel (b) presents the CDF of losses, with the actual Yasi event producing a AUD 26.5 million loss and ranking at percentile 26.5. This translates into a 73.5% chance of a counterfactual-Yasi producing higher losses than the realised event just based on arrival time and a potential to cause a maximum of AUD 296.3 million in losses, an order of magnitude higher.

3.2 Perturbing the landfall location

The second counterfactual condition we analyse is landfall location. We considered 204 tracks where the landfall point is shifted along the coastline in 2 km increments

404 from the original landfall location in both directions up to a range of ± 175 km. These
 405 location-shifted tracks maintain the same timing, intensity and orientation (i.e., 0°
 406 bearing angle) as the actual Yasi. To isolate the effect of storm surge, these hydro-
 407 dynamic simulations were run without any tidal forcing, i.e. only wind and pressure
 408 forcing. Therefore, these initial results can be interpreted as a simple version of the
 409 “non-tidal residual” (NTR), i.e. the storm surge rather than the storm tide, disre-
 410 garding any nonlinear tide and surge interaction effects. We made this decision given
 411 the infeasibility of running $204 \times 2,688$ hydrodynamic simulations to obtain a fully
 412 nonlinear analysis of landfall location and time.

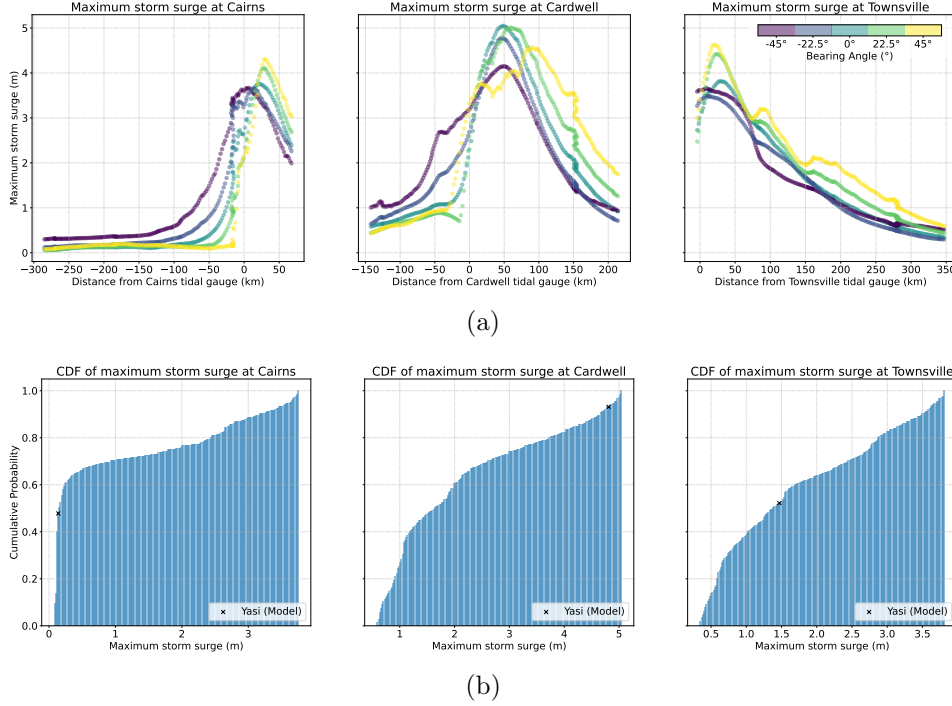


Fig. 6 Analysis on storm surge for different Yasi landfall locations and bearing angles. (a) Distribution of maximum storm surge at the tide gauges of interest given the distance to landfall location (positive distance to the north). (b) Cumulative distribution function (CDF) of storm surge at the relevant tide gauges for the 0° bearing angle (i.e., the original track’s bearing).

413 Storm surge is shown in Fig. 6 panels (a) as a function of the distance from the
 414 landfall location to each tidal gauge of interest. Note that distance northwards² is
 415 denoted by positive numbers, and southwards is negative. Since the storm tide simu-
 416 lations were run simultaneously for all 5 bearing angles (see next section), panel (a)
 417 includes all the curves. In this section we focus only on the 0° bearing angle.

² “Northwards” is used intentionally loosely here, since landfall points follow the coastline, which has a variable orientation. Therefore, it must be understood as following the coastline towards the north-most point.

For all three locations, the curves show a clear peak, meaning that we cover the maximal event for each location in this set. The peak at the Cairns gauge occurs for a landfall at +21.6 km from the gauge, for the Cardwell gauge it is at +47.2 km, and for the Townsville gauge it is at +32.7 km. Due to the clockwise rotation of tropical cyclones in the southern hemisphere, the largest storm surges occur when the TC makes landfall northwards of the point of interest. In addition, storm surges have a sharper decline from the maximum as the TC moves southwards (i.e., towards the negative distances). Panels (b) present the storm surge for all 204 simulations of the 0° bearing angle as a cumulative distribution function. The track with the actual landfall location is denoted with a black cross. The maximum storm surge across all counterfactual events occurs at the Cardwell gauge, with a peak value of 5.05 m, followed by Townsville (3.81 m) and then by Cairns (3.76 m). The storm surge of the actual Yasi event (modelled) was 4.81 m at Cardwell, ranking at the 93.2 percentile. This indicates that Yasi made landfall at almost the worst possible location for Cardwell, though the low-tide landfall time mitigated the effects, as discussed in the previous section. The NTR at Townsville is 1.47 m, in the 52.2 percentile. Being far to the north of the landfall location, Cairns only sustained a NTR of 0.14 m, which corresponds to the 47.8 percentile. However, the CDF is very steep up to the 60th percentile in Cairns (i.e., NTR is low and barely changes), since most of the landfall points fall south of the city. NTR increases sharply after landfall occurs in the vicinity of Cairns.

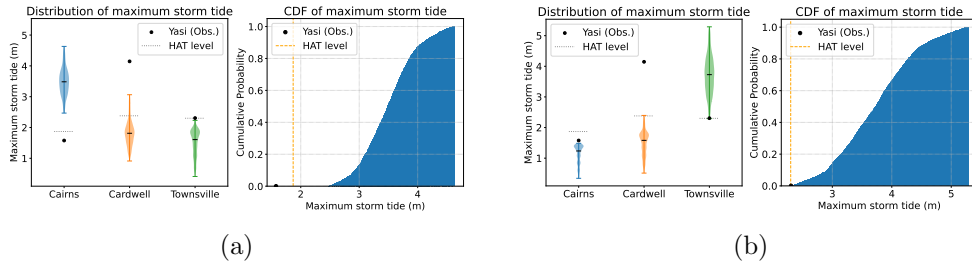


Fig. 7 Distribution and cumulative distribution function of maximum storm tide for different Yasi landfall locations. (a) Landfall in Cairns. (b) Landfall in Townsville.

The tracks with the landfall locations giving the largest storm surges at Cairns and Townsville were selected to perform a full 28-day period analysis analogous to the one presented in the previous section, with 2,688 simulations run for each track (with start times spaced 15 minutes apart), in order to investigate what the worst possible outcomes could have been for these 2 cities. Further analysis for Cardwell was disregarded, given the relatively small difference (24 cm) between the actual Yasi landfall, which has just been analysed, and the worst-case scenario.

Fig. 7 presents the distribution of maximum storm tide at the three gauges of interest for a landfall at Cairns (panel a) and at Townsville (panel b), together with the cumulative distribution function at each city. In both instances the storm tide exceeds HAT and the observed Yasi storm tide values for all landfall times. This

450 highlights that a Yasi-like storm making landfall immediately north of either city would
 451 produce inundation regardless of the tidal phase, with this component controlling the
 452 inundation severity. In addition, because no counterfactual scenario floods both cities
 453 simultaneously, impacts are largely confined to each targeted city. The worst case can
 454 therefore be assessed separately for each city.

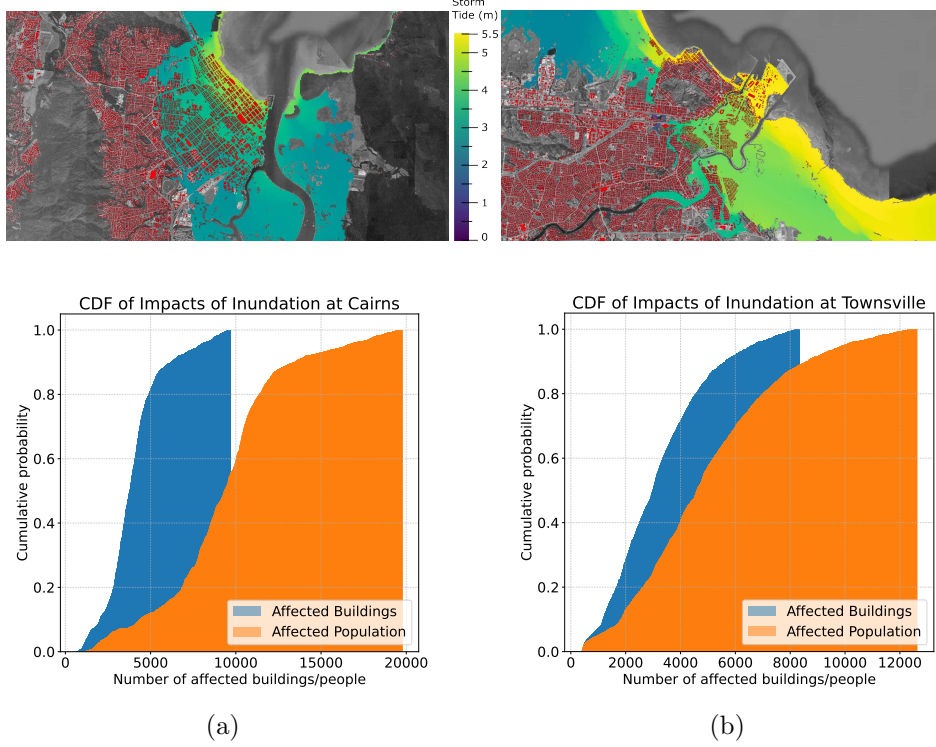


Fig. 8 Tidal cycle analyses for a 0-degree bearing angle landfall at (a) Cairns, (b) Townsville. Maximal inundation footprint envelope (top row) and impacts of inundation (bottom row).

455 Fig. 8 presents the maximal inundation footprint (top row) and the impacts on
 456 buildings and population (bottom row) for Yasi-like tracks landfalling at Cairns and
 457 Townsville. The inundation maps show a significantly larger inundation extent with a
 458 substantial urban inundation component both in Cairns and Townsville, in contrast to
 459 Fig. 4, in which landfalling occurred at the original location near Mission Beach. This
 460 directly translates into significantly higher impacts (bottom row), which we should
 461 note are still computed over the same domain of interest as before. The number of
 462 affected buildings when landfall occurs in Cairns can reach a maximum of 9,684, and
 463 8,344 when it occurs in Townsville, approximately double the number of buildings
 464 affected for the most damaging tidal phase at the original landfall location. When
 465 comparing the results in Fig. 8 against those in Fig. 3, there are two main differences.
 466 First, the CDF is steeper for Cardwell, indicating that the inundation in Cairns and
 467 Townsville leads to a more progressive increase in impacts, probably reflecting the

468 higher urban densities in those two cities. The second observation is that the size of
 469 affected population in Cairns (19,774) and Townsville (12,626) is not only larger in
 470 magnitude than in Cardwell (5,046), approximately 3.9 and 2.5 times greater, but also
 471 significantly larger when benchmarked against the number of buildings affected. This
 472 reflects the fact that multi-family dwellings are more common in these larger cities
 473 than in Cardwell.

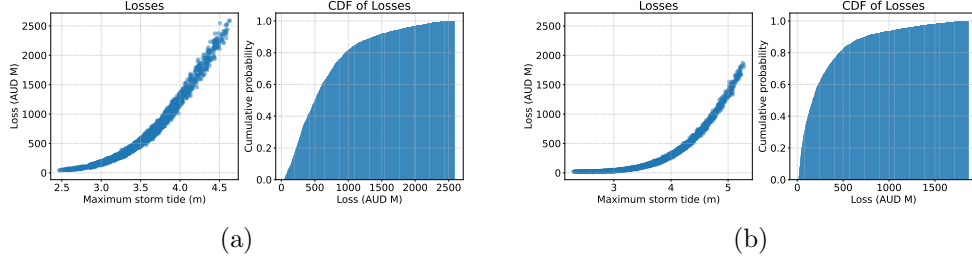


Fig. 9 Analysis on economic losses for landfalls at (a) Cairns and (b) Townsville over a 28-day period. Correlation with storm tide on the left subpanel and cumulative distribution function on the right subpanel.

474 The larger impacts for landfalls in Cairns and Townsville also translate to larger
 475 losses, as shown in Fig. 9. The relationship between maximum storm tide and losses is
 476 exponential and shows little scatter. This reflects the nonlinearities of loss calculations.
 477 First, as water levels rise, inundation progresses further inland and more properties are
 478 inundated. And second, due to the shape of the damage functions relating inundation
 479 depth to loss, which typically rise slowly at very low depths but then increase rapidly
 480 once damaging depths are reached. Based on our analyses, the maximum loss for a
 481 Yasi-like event in Cairns is as high as AUD 2.59 billion, nearly 100 times more costly
 482 than the estimate using the actual Yasi track in this study, and approximately 9 times
 483 the maximum event at Cardwell. The maximum loss in Townsville is 28% smaller than
 484 in Cairns: AUD 1.87 billion. Yet, this is 70 times more costly than with the actual
 485 Yasi track and approximately 6 times the maximum event at Cardwell.

486 The results so far highlight that Yasi had a potential to increase losses by an order
 487 of magnitude just by changing its landfall time within a narrow 28-day window. By
 488 considering the same storm landfalling near Cairns or Townsville – both locations
 489 within the original cone of uncertainty – that potential loss increases by another order
 490 of magnitude.

491 3.3 Perturbing the track bearing at landfall

492 The final analysis considers counterfactual scenarios in which Yasi not only made
 493 landfall at different locations and times, but also with different angles of attack at
 494 landfall, by simply rotating the complete track centred at the landfall location. Given
 495 the unmanageable number of simulations required to perform a fully nonlinear analysis
 496 ($5 \times 204 \times 2,688$), we instead developed a surrogate model to simulate the nonlinear

surge-tide interaction (see Appendix B for a complete description), so the methodology applied differs slightly from the previous analyses.

Storm surge results for all 5 bearing angles have already been shown in Fig. 6 panels (a) as a function of the distance from the landfall location to each tidal gauge of interest. For Cairns and Townsville gauges, positive bearing angles (i.e. clockwise rotation) increase the storm surge, with $+45^\circ$ leading to 4.31 m and 4.63 m, $+22.5^\circ$ leading to 4.10 m and 4.32 m, all above the third highest values derived from the original 0° bearing angle, which led to 3.76 m and 3.81 m, respectively. The order is different in Cardwell, where 0° yields the highest storm surge (5.05 m), closely followed by $+22.5^\circ$ leading to 5.01 m and -22.5° leading to 4.77 m. This reinforces the idea that the actual Yasi was very close to the worst case possible for Cardwell, if not for its landfall timing close to low tide. However, in this final analysis we focus only on Cairns and Townsville again, since they have the potential to suffer from higher economic losses.

We picked the cases giving the highest storm surges from amongst the top 3 bearing angles at the Cairns and Townsville gauges, referenced above, and reran these with tidal forcings for a 28-day period, resulting in 2,688 simulations each (with start times spaced 15 minutes apart), to obtain fully nonlinear storm tide results. We also ran a tide-only simulation over the same period to act as a benchmark. The data produced was used to fit two linear models that can predict storm tide at Cairns and Townsville gauges, given the local storm surge and tides at any time. Despite storm tide being nonlinear in nature, the degree of non-linearity is minimal enough that linear approaches work well, with an R^2 above 0.996. Full details of the linear models are given in Appendix B.

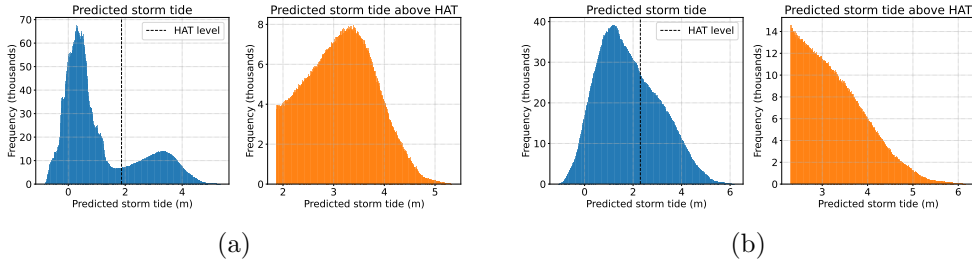


Fig. 10 Distribution of storm tide from the linear surrogate model. Complete distribution on the left subplot, distribution of events above HAT on the right subplot. (a) Cairns. (b) Townsville.

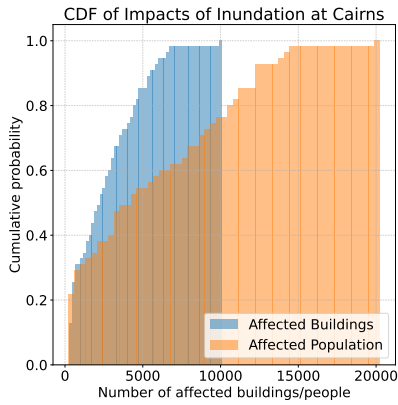
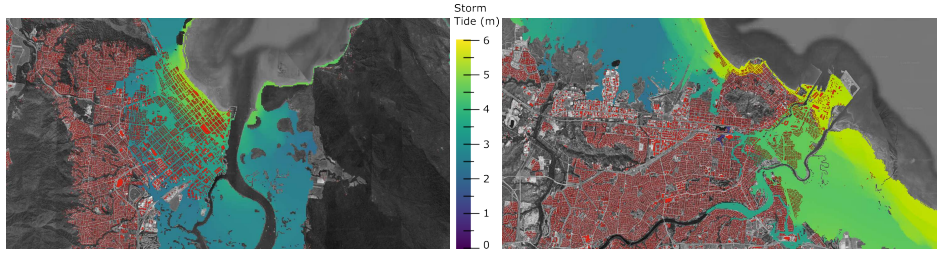
The linear models were then applied as a surrogate model of storm tide to predict a time series for each of the $5 \times 204 \times 2,688$ scenarios (for a total of 2,741,760 scenarios) referenced at the start of this section and the results are analysed in Fig. 10, for Cairns (panel a) and Townsville (panel b). The distribution of the maximum in time for each of the scenarios is presented in the left subplots, whereas the distribution of cases exceeding HAT are shown in the right subplots. The distributions at each location, which look very different, are the result of local conditions (bathymetry, tidal range and storm surge) leading to nonlinear effects. In Cairns only 25% of the cases are

529 above HAT, and the distribution is markedly bimodal, with a strong peak below HAT
530 at approximately 0.3 m, and a smaller peak above HAT at approximately 3.3 m. In
531 Townsville the distribution only has a single peak, at 1.2 m, below HAT, and a larger
532 proportion of the cases (34%) are above HAT.

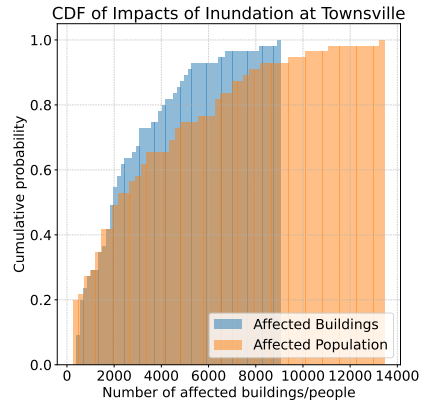
533 Among all cases above HAT, 11 were picked for each of the 5 bearing angles at
534 Cairns and Townsville to calculate losses. The selection was based on choosing the
535 cases that were the closest to the 10th percentiles of storm tide (from 0th, the minimum
536 close to HAT, to 100th percentiles, the maximum overall), leading to a small subset
537 of $2 \times 5 \times 11$ events that is representative of the complete range above HAT. These
538 cases were run in MIKE 21 HD FM to obtain fully nonlinear storm tide results (which
539 have also been used for the validation of the linear model, see Appendix B) and in the
540 inundation model to obtain their corresponding inundation footprints.

541 The envelope of inundation (maximum extent and inundation depths) among the
542 final set is presented in the top subpanels in Fig. 11. The inundation extent and depths
543 are larger when compared to those in Fig. 8, by +24.6% and +14.7% on average,
544 respectively. This translates into slightly larger maximal impacts, at both locations
545 (bottom subpanels). The worst case for a landfall in Cairns leads to a maximum of
546 10,071 buildings and a population of 20,247 affected, up from 9,684 and 19,774 from
547 the previous section. The worst case for Townsville shows a similar trend, with 9,069
548 buildings and a population of 13,472 affected, up from 8,344 and 12,626 when not
549 changing the bearing angle.

550 The distribution of losses per bearing angle for landfalls at Cairns and Townsville
551 is shown in panels (a) and (b) in Fig. 12. In general, the majority of the losses are
552 distributed below AUD 500 million which is consistent with the large proportion of low
553 storm surge values in the top subpanels in Fig. 6, and the marked correlation between
554 storm tide and losses (see Fig. 9). The only median loss above this mark is for +45° in
555 Cairns, which presents a wider distribution of losses. In addition, the maximum losses
556 for each bearing angle are also in accordance with the maximum storm surge values
557 in Fig. 6, except for +22.5° in Townsville. This is likely caused by random effects due
558 to the low number of cases selected for each bearing angle, since the scatter shown in
559 the validation of the linear model is significant (see Appendix B). While the maximum
560 losses obtained for the 0° bearing angle in Fig. 12 are smaller than those in Fig. 9
561 for the same reasons, the global maxima at Cairns (AUD 2.91 billion) and at Townsville
562 (AUD 2.31 billion), both for +45° bearing angle, are still larger than the maxima found
563 for the previous analysis, by 12% in Cairns (AUD 2.59 billion) and 24% in Townsville
564 (AUD 1.87 billion).

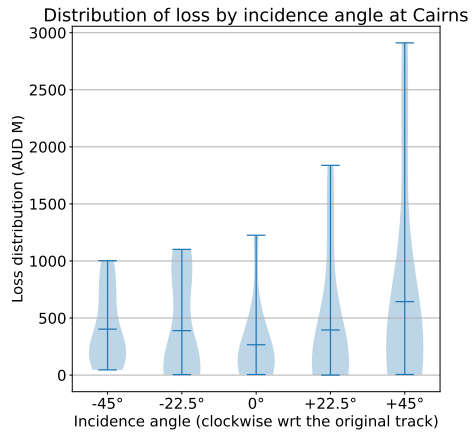


(a)

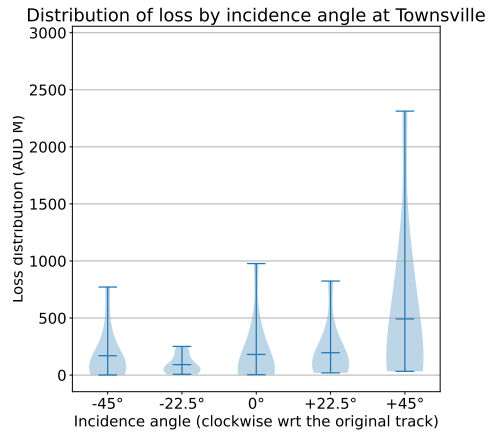


(b)

Fig. 11 Analyses for cases among the top 3 bearing angles and landfall at (a) Cairns, (b) Townsville. Maximal inundation footprint envelope (top row) and impacts of inundation (bottom row).



(a)



(b)

Fig. 12 Distribution of economic losses as a function of the bearing angle for landfalls at (a) Cairns and (b) Townsville.

4 Discussion

It is challenging to estimate the risk of dangerous flooding from storm surges at a given location, when events in history are relatively rare. Infrequent, extreme weather events can be thought of as being random samples from an underlying distribution of possible outcomes; in this study we explored the plausible parameter space around a realised event, TC Yasi, to gauge how bad its potential impact could have been, measured both in terms of hazard severity and economic damage due to storm surge. In doing so, we have highlighted how sensitive the economic damage is to the precise tidal phase at the time of landfall, as well as the critical difference made by the location of landfall. Our interpretation of the results of this sensitivity analysis have been based on the assumption that the counterfactual events we consider correspond to plausible scenarios.

A perturbation analysis on landfall time alone during a 28-day period indicated that the likelihood of a more severe event in Cardwell, if the landfall time is chosen at random, is 81.8%, and that losses could have increased by an order of magnitude. This underlines how lucky the local population was that Yasi's impact was mitigated by landfall occurring close to low tide. Landfall location was found to be very important too, since TC landfalling at areas of very large exposure (i.e., Cairns and Townsville) had a major impact on losses. The location plus timing analyses showed that the maximum loss is higher for Cairns than for Townsville, and is one order of magnitude higher than the maximum for a Cardwell landfall, and therefore, two orders of magnitude higher than the original Yasi scenario. The final analysis highlights that changing the bearing angle of the storm at landfall also has the potential to further increase the losses, albeit by a smaller amount than varying landfall timing or location, with increases between 12% and 24%. It should be borne in mind that for the cases we have illustrated in which the worst possible storm surge and tide combinations occur simultaneously, the return period of the event would be significantly longer than if these were independently picked at random.

There are several factors which have not been considered in this study and have the potential to increase the hazard and losses even further. One such factor is the influence of the nodal tidal cycle, which could noticeably increase the total water levels during a storm surge event, as described in Appendix A. Two other factors are wave setup and runup, which can contribute to higher total water levels during a storm surge event and which require further detailed and computationally-costly modeling to accurately estimate their impact. Long term sea level rise associated with climate change is also likely to contribute to higher water levels over the coming decades, though we note the magnitude of this phenomenon (cm's per decade) is significantly smaller than the tidal ranges and storm surges involved here; as such the conclusions of this study are broadly unaffected by sea level rise on a timescale of years-to-decades into the future. In addition, compound events, such as the simultaneous occurrence of heavy rainfall and storm surge, can lead to significantly higher losses than either event occurring in isolation. However, modelling these compound events is complex[39] and beyond the scope of this study focused solely on storm surge.

Finally, we remark that existing studies have also addressed some factors that impact storm intensity, for example sea surface temperature (SST). Lavender et al.[17]

conclude that “if TC Yasi had occurred during non-La Niña conditions the associated storm surge may have been greatly diminished, with a decrease in storm surge height of over 3 m when the SST is reduced by 2°C”. In this study, we chose to focus on the more aleatoric aspects of track characteristics, rather than changes in intensity or other track-related meteorological parameters to avoid departing too much from the assumption of plausible counterfactual events. However, we acknowledge it is also important to consider the full range of possible storm intensities and sizes when carrying out a risk analysis. Indeed, the basis for catastrophe modelling – the framework widely used throughout the global insurance industry to quantify and price disaster risk – is to build a stochastic event set spanning the full range of possible cyclone intensities, sizes, locations and timings[10].

In conclusion, counterfactual analyses such as the present study can complement catastrophe models, both by acting as a stress test for them, and also to help show disaster planners and the wider public what a plausible event could potentially look like.

Data availability. All of the environmental, topographic and exposure datasets used to build and force the models in this study are publicly available from their original providers, as cited in the paper.

Two groups of data underlying the results are *not* publicly available. First, the 2026 Moody’s Australia Cyclone HD Economic Exposure Database and the vulnerability functions of the Moody’s Australia Cyclone HD Coastal Flood model are proprietary commercial products of Moody’s, are licensed to clients under contract, and cannot be redistributed by the authors; consequently, no property-level exposure, damage or loss output can be shared. Second, the bare-earth corrected Digital Elevation Model produced with Moody’s in-house machine-learning methodology is a derived proprietary dataset.

The derived, aggregated data that support the findings and figures of this paper are available from the corresponding author on reasonable request. These include the counterfactual track definitions (landfall location, landfall time and bearing perturbation for each ensemble member), the modelled peak storm surge and peak storm tide at the Cairns, Cardwell and Townsville gauge locations for every ensemble member, the fitted surrogate-model coefficients, and the ensemble summary statistics (percentiles, medians and maxima of inundated area, population affected and modelled loss) plotted in Figures 2–14.

Code availability. The coastal ocean hydrodynamics were simulated with MIKE 21 HD FM, commercial software available from DHI (<https://www.mikepowerebydhi.com>). The unstructured computational mesh was built with the openly available *seamsh* Python API[23] and the open-source *gmsh* mesh generator[24], <https://gmsh.info>. The two-dimensional shallow-water overland inundation solver is a proprietary in-house tool developed by Moody’s. The Moody’s Australia Cyclone HD Coastal Flood model is proprietary commercial software developed and licensed by Moody’s (<https://www.moody.com/web/en/us/capabilities/catastrophe-modeling.html>).

653 The commercial products cannot be released publicly or made available for review.
654 The numerical methods they implement and publicly available details are specified in
655 the text of the paper.

656 The scripts used to generate the counterfactual track set, to post-process the model
657 output and to produce the figures were written in Python using open-source libraries
658 only, and are available from the corresponding author on reasonable request.

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660 for their comments on earlier versions of this manuscript.

661 The Australia high resolution population density maps used in this study are
662 derived from the High Resolution Settlement Layer (HRSL) of Facebook Connectivity
663 Lab and the Center for International Earth Science Information Network (CIESIN),
664 Columbia University[36]; source imagery for HRSL © 2016 DigitalGlobe.

665 Satellite imagery used as a basemap in Figures 4, 8 and 11 from Google Earth:
666 ©2026 Airbus, CNES / Airbus, Landsat / Copernicus, Maxar Technologies, Vexcel
667 Imaging US, Inc.

668 **Author contributions.** C.J.T. and P.H. conceived the study and designed the
669 counterfactual ensemble. C.J.T. generated the perturbed tracks. All authors developed
670 the launching and processing scripts for the model. P.H. ran the coastal hydrodynamic
671 model and inundation model and performed the formal analysis of the results. C.J.T.
672 and P.H. wrote the first draft of the manuscript and produced the figures. All authors
673 reviewed, edited and approved the final manuscript.

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676 **Competing interests.** The authors declare the following competing interests. P.H.
677 and S.P. are employed by Moody’s, and C.J.T. was employed by Moody’s while
678 this research was carried out and is now employed by Aon. Both organisations are
679 commercial providers of catastrophe risk models, analytics and services to the insur-
680 ance and reinsurance industry. The hazard, exposure and loss results presented here
681 were produced with commercial Moody’s proprietary assets: the Moody’s Australia
682 Cyclone HD Coastal Flood model, its vulnerability functions and Economic Exposure
683 Database. No external party had any role in the study design, in the collection, analy-
684 sis or interpretation of the data, or in the decision to submit the work for publication.
685 The authors declare no other competing interests.

686 Appendix A – Tidal characteristics at Cairns, 687 Cardwell and Townsville

688 Tide levels are an important factor that influences the inundation potential of the
689 storm surge events. In Fig. 13 we present the characterization of modelled tides at the
690 Cairns, Cardwell and Townsville tide gauges for two periods. The first one (“complete
691 period”, in blue) is 18.6 years long and covers the full nodal cycle, effectively providing
692 the highest modelled tides. The second period (“Yasi period”, in orange) covers the

14 days before and after Yasi landfall, capturing the highest tides that the tropical cyclone (TC) could have reasonably experienced.

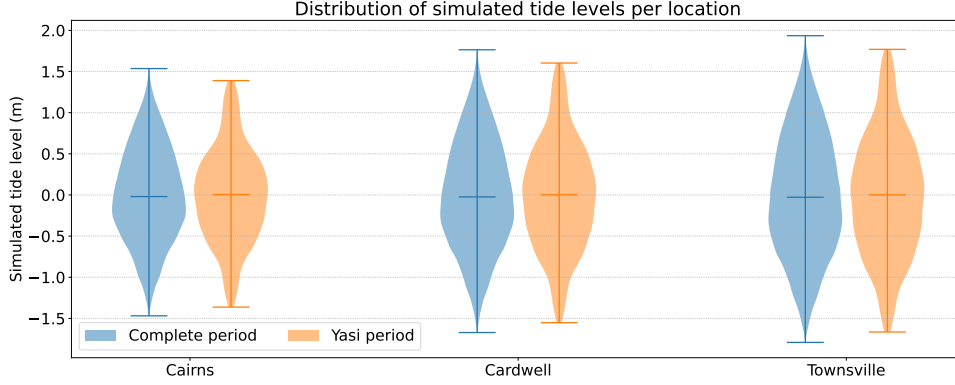


Fig. 13 Distribution of tide levels at the Cairns, Cardwell and Townsville gauges for the full 18.6-year nodal cycle (in blue) and 14 days at each side of Yasi landfall (orange).

At these three locations, the maximum tidal level during the Yasi period is within the 61st to 63rd percentiles of maximum monthly values obtained during the complete period. This means that the maximum water levels during Yasi period are much closer to the median than to the maximal levels of the nodal cycle and that the total water levels obtained in this paper have the potential to be even higher, had Yasi occurred at the peak of the nodal tidal cycle. In absolute terms, the differences between the full nodal-cycle maximum and the Yasi-period maximum tide are 14.7 cm in Cairns, 16.1 cm in Cardwell and 16.6 cm in Townsville. However, in this paper we have constrained the analysis to the actual timing of TC Yasi, without accounting for the potential variations introduced by the nodal tidal cycle.

We generally consider the Highest Astronomical Tide (HAT) as the threshold above which major coastal inundation may start occurring. Specifically for TC Yasi, Queensland Government post-event survey reported a 5.33 m peak storm surge at falling tide at Cardwell[40], which pushed total water levels to 2.23 m above HAT. At Cardwell, HAT is reported as 2.44 m above the Australian Height Datum (AHD)[41], corresponding to 2.38 m above EGM2008 (Earth Gravitational Model 2008). This is the HAT value adopted in this work, with EGM2008 used as the vertical datum. The same source reports the Lowest Astronomical Tide (LAT) at Cardwell as 1.86 m below AHD, yielding a 4.30 m tidal range. Here, we highlight a slight discrepancy for the reported HAT levels at Cardwell tide gauge between both sources. The post-cyclone report[40] records HAT as 4.13 m above LAT, thus yielding HAT as 2.27 m above AHD. This is 17 cm below the value reported by the Queensland Government tide monitoring sites

website[41]. The rest of HAT values used in this work, which are extracted from the
Queensland Government tide monitoring sites website³ are shown in Table 1.

Table 1 Highest astronomical tide (HAT) values adopted in this work. Datum: EGM2008.

Location	HAT (m)
Cairns	1.87
Clump Point	1.97
Cardwell	2.38
Townsville	2.30

Appendix B – Storm tide linear model for Cairns and Townsville

Storm tide calculation generally requires costly hydrodynamic simulations to capture nonlinearities from the interaction of tides and storm surge. The final counterfactual analysis performed in this work would require almost 2.75 million hydrodynamic simulations, which is not manageable in terms of computational resources, time and storage. Therefore, we developed two separate linear surrogate models for peak storm tide at the Cairns and Townsville tide gauges.

At each location, we selected three scenarios for which the storm surge response had already been simulated without tides. These scenarios correspond to the highest storm surge among the top 3 bearing angles, and were chosen to capture the potentially stronger nonlinearities from large surge responses. For each scenario, we ran hydrodynamic simulations with tidal forcing for a 28-day period every 15 minutes, to obtain fully nonlinear storm tide results. The total number of simulations per location is 8,064 ($3 \times 2,688$). We also ran a tide-only hydrodynamic simulation for the same period, from which we obtained the time series of tide elevation, and calculated its rate of change (ROC) using central differences.

For each location, the model predicts the nonlinear peak storm tide from three covariates: the peak storm surge, the tidal elevation at the time of peak storm surge, and the rate of change (ROC) of the tide at the time of peak storm surge. Model fitting minimized the root mean square error (RMSE) between predicted and simulated peak storm tide. The surge and storm-tide peaks occurred at the same time in virtually all simulations. In the few exceptions, they differed by one 15-minute interval. This close temporal correspondence supports the use of tidal conditions at the time of peak surge as model predictors.

The fitted linear models are:

³<https://www.qld.gov.au/environment/coasts-waterways/beach/storm/storm-sites/X> where X is cairns, clump-point, cardwell, or townsville as appropriate.

$$\begin{aligned} \text{Peak_Storm_Tide}_{\text{Cairns}} = & 0.975 \text{Peak_Storm_Surge} + 0.734 \text{Tide_Elev} \\ & - 140.075 \text{Tide_RoC} + 0.113 \end{aligned} \quad (1)$$

$$\begin{aligned} \text{Peak_Storm_Tide}_{\text{Townsville}} = & 0.973 \text{Peak_Storm_Surge} + 0.832 \text{Tide_Elev} \\ & - 1971.023 \text{Tide_RoC} + 0.102 \end{aligned} \quad (2)$$

Here, Tide_RoC is expressed in m/s. All other predictors and the response are elevations expressed in metres. The models achieved $R^2 = 0.997$ for Cairns and $R^2 = 0.996$ for Townsville on the fitting data. The peak storm surge coefficients and intercepts are similar at the two locations. Training a model in which the intercept was constrained to zero resulted in peak storm surge coefficients virtually equal to 1, with negligible changes to the other coefficients or performance. This suggests that the intercept could be omitted by counterbalancing the peak storm surge coefficients without significantly affecting the model's predictive capability.

The tidal elevation coefficients are also comparable between both locations and are both below unity. Thus, when peak surge coincides with high tide, when the tidal ROC is zero, the resulting storm tide is noticeably smaller than the sum of the peak storm surge and the tidal elevation.

The largest difference between the models is in the coefficient of tidal rate of change. In both instances, the coefficient is negative, indicating that for otherwise equal predictor values, the models predict a higher peak storm tide when peak surge occurs on a falling rather than a rising tide (i.e., a falling tide enhances the peak storm tide). The magnitude of this coefficient is approximately 14 times greater in Townsville than in Cairns. Although tidal ranges are relatively similar, they are slightly larger in Townsville (Fig. 13). The maximum ROC of the tide for the 28-day period modelled is also comparable between both locations, with the maximum value in Townsville ($2.51 \cdot 10^{-4}$ m/s) being approximately 29% higher than in Cairns ($1.94 \cdot 10^{-4}$ m/s). At these rates, maximum storm tide enhancements due to ROC differ by an order of magnitude, namely, 0.03 m in Cairns and 0.49 m in Townsville.

These fitted relationships indicate that peak storm tide has a larger potential to be higher in Townsville compared to Cairns. As broader context, [42] (Appendix E) reports theoretical maximum storm tides of 8.07 m above AHD for Cairns and 11.23 m above AHD for Townsville.

Figure 14 compares peak storm tides from the hydrodynamic simulations (horizontal axis) with linear model predictions (vertical axis). On the fitting data (left panels), agreement is particularly close for Townsville (panel b), whereas the Cairns model (panel a) slightly underestimates the lowest and highest values.

On the held-out cases (right panels), both models capture the overall trend but show greater scatter, with errors of approximately $\pm 20\%$ for some of the largest storm tides. This level of accuracy is appropriate for the models' limited purpose: selecting cases for the final counterfactual analysis. We remark that all impact and loss estimates reported in this paper instead use results from hydrodynamic simulations that resolve nonlinear tide and surge interactions.

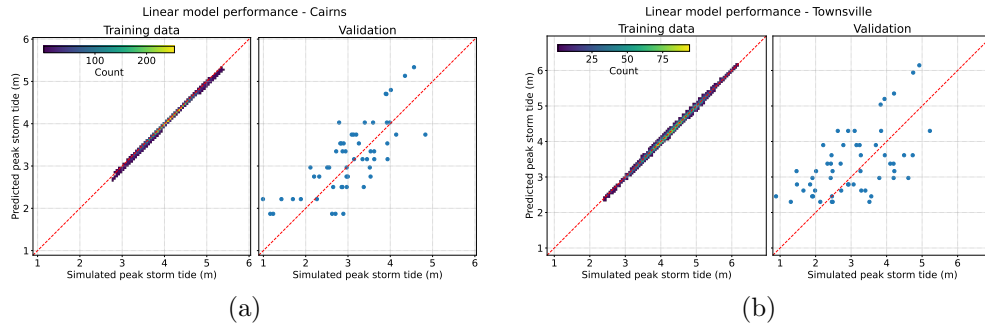


Fig. 14 Linear model performance for peak storm tide at (a) Cairns and (b) Townsville. Verification against training data (left subpanel) and validation against unseen cases (right subpanel).

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