Document addressing reviewer comments

- The manuscript provides a framework for comparing TC-related risk across Australia, incorporating multiple hazards, multiple exposure elements and multiple indicators of vulnerability.
- The framework described is a relative risk rating, based on a limited view of the probability of events (i.e. a 1% AEP level of hazard) in combination with national-scale indicators of exposure and vulnerability.
- Similar efforts have been undertaken within government in recent times, but are as yet unpublished. This manuscript provides a stimulating discussion on the complexity of evaluating multi-hazard risk in a nationally-consistent framework.
 - Properly undertaken, the resulting information from this analysis could be valuable for prioritising interventions across the country.
- The derivation of some metrics warrants further discussion the range of spatial scales presents unique challenges to developing representative rankings of hazards, especially with relatively coarse information. Flood and storm surge inundation are highly sensitive to spatial resolution, and will be challenging to represent at LGA resolution.
 - The elements of exposure and vulnerability must be linked using social vulnerability indicators in combination with physical asset exposure will not produce a valid evaluation of risk (either physical or social).

Dear Reviewer, thank you for your valuable comments which helped us to improve quality of the manuscript. All your comments have been addressed in a revised version of the manuscript. We hope you will find this revision satisfactory.

- 25 This is the ideal, having multiple vulnerability indicators specific to each exposure indicator, as well as tailored to each specific hazard, but due to limitations in data availability, a more general estimated approach was taken to estimate exposure as the combination of populations and built infrastructure, with vulnerability indicators of IRSD, vulnerable age groups etc. referring to that general exposure. Infrastructural vulnerability indicators were sought, but data not found to be available. We have added discussion of this limitation into the revised manuscript at the end of section 3.1.
 - We have concerns over the evaluation of risk, showing highest risk in northern NSW, including some LGAs well inland where wind hazard will be declining, there is no surge hazard and flood hazard is evaluated to be in the lowest quintile.
- At first this was thought to be due to high exposure values, but upon further inspection, hazard values in this high risk area actually have significant index values of ~0.4-0.7 despite original hazard maps suggesting they are in the lowest natural breaks class of hazard. As a result, hazard maps (as well as exposure and vulnerability indicator maps) have had a symbology change from natural breaks to quantile (decile for hazard and quintile for exposure/vulnerability). This depicted representative trends that are transferred over into risk calculations, and shows hazard to actually be quite high for flood in particular over NSW/lower QLD. This stark difference was because hazard values had not been normalised in the map to keep information for surge and wind (surge

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	height and wind speed), however using natural breaks for data with values with very
45	different magnitudes at min and max boundaries did not align with processed values that
	were used in risk index calculation (decile normalised values). In the revised manuscript,
	maps have been updated to a quantile symbology, and for hazard, descriptive values have
	been kept, but now the e.g. 2 nd highest decile (2nd darkest blue) is equivalent to 0.8 while
	highest/darkest is equivalent to 0.9 in the risk calculations.

- Sections Method, Results and Discussion have been updated to reflect these changes. The Quantile symbology has been used for exposure and vulnerability indicators as well, however the trends/findings from the maps have not changed, as indicator data had already been transformed into a decile format.

55 Specific comments and questions for the authors:

• Line 78: Only one ARI is used - the relative impact may change for different return levels due to the different spatial pattern in hazard and/or vulnerability. Do the authors have any comments on this?

One ARI return period was used due to data availability. Although some hazard datasets had more ARI periods available, 100 years was chosen as it was available for all chosen hazards.

• Line 79: It is not appropriate to say this is representative of the hazards in the near future. The 100-year ARI hazard level is an indication of the long term probability in that it occurs - on average - once in every 100 years. There is a possibility of such an event occurring in any given year (approximately a 1% probability), with no inference about the near future likelihood. Further, the 100-year return period level may well change over the next 100 years. Knutson et al (2020) report the most confident TC-related projection is increased storm surge levels, with medium to high confidence that TCrelated precipitation will increase at the global scale.

This has been revised, removing 'in the near future' and adding that it is the 100-year ARI level at the moment and is predicted to change in the future.

• Section 2.1: There is not sufficient discussion on the metrics used for the hazard indices. No references are provided for flood or landslide hazard information in the main part of the manuscript (a table is presented in the appendix, but it is not referenced, and the links in the table are not accessible); the reference provided for Storm Surge does not describe that hazard ("For this global study, the effects are only related to the wind speed at a global scale." Cardona et al., 2014). This is a major concern to the core objectives of the manuscript.

The data table has been moved to the main part of the manuscript (as per another reviewer's comments), and has now been referenced. Upon further inspection of information attached to the surge data taken from GAR Atlas' risk data platform, Cardona and Bernal references do not seem to align, and at the moment it is unsure which company/researchers created it. As a result, GAR Atlas has been referenced, and a more detailed description of the surge data is included under the methods hazard section, along with more descriptions of wind/landslide/flood input data.

 Line 80: There are more up-to-date sources of information for storm tide hazard - e.g. the Canute 3.0 data available through the NESP Climate Hub (https://shiny.csiro.au/Canute3_0/)

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We were not aware this existed at the time of conducting the study, and the surge data from GAR Atlas fit our methods and was easy to summarise to LGA level. More up to date data will be considered for future work trying to improve upon the hazard index.

Line 81: Mean values of hazard may not be appropriate for some LGAs. This is an issue the authors note (in reference to East Pilbara). However, the hazard needs to be evaluated in the context of exposed assets. In the case of East Pilbara, the majority of exposed assets (primarily population) are close to the coastline, where wind hazard (and flood hazard) will be higher. In our comparative rankings, we have used a 90th percentile of the hazard level, reflecting the general proximity of population to the coastline.

This is a limitation that is discussed, however the approach we took was to apply an easily replicable methodology, using the same processes and calculations for all LGAs, rather than personally identifying outliers, and applying our own assumptions to them. This is because
interventions would require a strong understanding of all regions in Australia, and we would need to choose a cut off point for where we do not intervene. In this case, ideally a higher resolution would reduce the occurrences of large LGAs disguising the exact locations of high/low exposure such as in East Pilbara.

- Line 89: No reference to the table of data sources is provided.
- 105 References to data sources from past studies have been added in the table and reference list, and hyperlinks have been used for ABS/webpage sources.
 - Line 89: Power line and electrical substations will be highly correlated, so using both as input to the exposure definition will be unduly weighted to that infrastructure element.
- Correlations were also found between population and hospital density along with powerline and
 substation datasets. This is because these types of infrastructure are built to meet the demand of
 populations living there. It is true there are 3 infrastructure indicators vs one population indicator,
 but all are chosen as important and valuable assets, equally weighted in the exposure index
 calculation. As the trends in each dataset are very similar, removing one of powerline/substation
 indicators would not make a substantial difference to the index.
- Line 89: What power line information was used distribution lines or transmission lines? In some urban LGAs, there may be limited transmission network coverage, with power supplied through lower voltage feeder networks that may lead to biased estimates of exposure. The data table provided does not contain working links, so readers are not able to inspect those sources.
- 120 Transmission powerlines of high voltage electricity were used. The link should be provided this time. While yes, some LGAs where the larger transmission powerlines will not pass through will show lower exposure, transmission powerlines represent the powerlines we determined to be more valuable/critical, as dysfunction would power out the subsequent smaller distribution lines.
- 125
- Overall losses will be impacted by the value of lost income to businesses. With no business information included, this may lead to an underestimate of exposure in some areas.

This is exactly correct, and discussed in relation to the mining economy in WA, as well as in limitations of risk assessments being limited to the information of chosen indicators. In this case,

we prioritized human life and infrastructure, whereas another study for end users that areinterested in GDP and productivity of different industries would use relevant exposure indicators.

• Line 103: The choice of vulnerability indexes is not clearly linked to the choice of exposure indexes. In the Hazard-Exposure-Vulnerability framework, the vulnerability is directly related to the exposed assets. Using social vulnerability indicators and physical assets presents a logical mismatch between the two risk factors. Ideally, physical vulnerability indicators should be used that link the hazard to the exposed physical assets.

Roughly the same comment was made above, and has been addressed there. To summarise, we have noted that ideally exposure and vulnerability indicators are directly linked (social vulnerability -> populations, building code -> infrastructure), however due to limitations in data, this was not feasible.

- The "no vehicle homes" is duplicated in the contributing indicators in the IRSD indicators, so places undue weighting on this indicator. Additionally, the claim of "no vehicle homes" indicator being particularly relevant should be justified what evidence is there to support the assertion they are more susceptible to loss of life, especially given the very limited fatalities attributable to TCs in Australia? Further, evacuation is only a consideration in storm tide prone areas. Otherwise, the emergency services advice is to shelter in place (i.e. at dwellings that are built to modern codes). A better indicator of vulnerability would therefore be the proportion of houses that are not constructed to modern wind loading standards.
- 150 The possible duplication of no vehicle homes indicator with 'NOCAR' input in IRSD is discussed in the vulnerability discussion already. The point about an evacuation indicator for a historically non-lethal natural disaster to Australia is a good point, and we would prefer to have an indicator that tells us the vulnerability of the infrastructure that cannot be evacuated and historically is a big portion of the damages/loss.
- 155 This suggestion is incorporated stating that "Although this risk assessment highly values human life and safety, historically within Australia, TCs have caused very few fatalities in recent decades, and an indicator describing the vulnerability of infrastructure would be preferred. An alternative to 'no vehicle homes' vulnerability indicator could be the proportion of houses that are not constructed to modern wind loading standards. While this potentially useful indicator was not included in this study due to limited data availability, this could be a topic for future work. "
 - Line 274: The use of data with null values for some LGAs suggests additional effort is required to ensure consistent coverage either through alternate indexes or suitable estimations from other sources.
- 165 LGAs with null values were generally less populated/country LGAs, and were very uncommon (mentioned LGA of Maralinga Tjarutja was one of the only cases, with no data values for IRSD data from the ABS).
 - Line 307: Correct "main coastland"

Updated to 'mainland'.

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	Cameron Do and Yuriy Kuleshov
	Multi-hazard Tropical Cyclone Risk Assessment for Australia
185	
	The hyperlinks work on the word document we submitted – we will make a note to the publishers to ensure links are working in the next iteration of the manuscript.
180	• Appendix: None of the links in the table are accessible - appears the links have not been properly included in conversion to PDF. "Geosciences Australia" should be "Geoscience Australia"
	Scawthorn has had as many details as possible available added to it. Do and Kuleshov reference has been removed for a flood risk assessment reference (Amadio et al., 2019) rather than an Australian TC context, as the paper is still undergoing its publishing/acceptance process. Burston reference has been updated.
175	• Several of the references are incomplete or inaccessible e.g. Scawthorn et al., 2006, Do and Kuleshov, 2022, Burston et al. (missing journal name)
	Included a sentence specifying importance for hazard indicators as exposure/vulnerability indicators from the ABS are well validated.
170	• Line 377: ABS data would typically be well validated. Engagement with the ABS may have addressed the authors concerns over validation of the (vulnerability) indicators.

Natural Hazards and Earth System Sciences https://www.natural-hazards-and-earth-systemsciences.net/

Abstract

Tropical cyclones (TCs) have long posed a significant threat to Australia's population, infrastructure, and environment. This threat may grow under climate change as projections indicate continuing sea level rise and increases in rainfall during TC events. Previous TC risk reduction-assessment_efforts 195 have focused on the risk from wind, whereas a holistic approach requires multi-hazard risk assessments that also consider impacts of other TC-related hazards. This study assessed and mapped TC risk nationwide, focusing on the impacts on population and infrastructure from the TC-related hazards of wind, storm surge, flooding and landslides. Risk maps were created at the Local Government Area (LGA) level for all of Australia, using collated data on multiple hazards, exposure 200 and vulnerability. The results study-demonstrated that the risk posed by all hazards was highest for coastal LGAs of eastern Queensland and New South Wales followed by medium risk across Northern Territory and north-west of Western Australia., with flood and landslide hazards also affecting several inland LGAs. Further enhancement improvement and validation of risk maps developed in this study will provide decision-makers with the information needed to reduce TC risk, save lives and 205 prevent damage to infrastructure. The resulting maps of risk will provide decision-makers with the information needed to further reduce TC risk, save lives, protect the environment, and reduce economic losses

Comment [CD1]: Reviewer: acronym table

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Acronyms	
ABS	Australian Bureau of Statistics
LGA	Local Government Area
NSW	New South Wales
NT	Northern Territory
QLD	Queensland
<u>SEIFA</u>	Socio-Economic Indexes For Areas
<u>SA</u>	South Australia
TAS	Tasmania
TC	Tropical Cyclone
VIC	Victoria
WA	Western Australia

210 **1. Introduction**

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Tropical Cyclones (TCs), also known as hurricanes or typhoons, are powerful and highly destructive meteorological hazards. Since 1970, almost 2,000 natural disasters have been attributed to TCs, which has led to over 700,000 deaths worldwide (World Meteorological Organisation, 2021). Costing about U.S.\$26 billion annually in global damages (Mendelsohn et al., 2012), their impact is expected to multiply to U.S.\$60 billion annually by 2100 (Bakkensen and Mendelsohn, 2019).

The proportion of intense TCs (Saffir–Simpson scale categories 4-5 with >209km/h-1-minute maximum sustained winds >209km/h) and peak wind speeds of the most intense TCs are projected to increase at the global scale with increasing impact of global warming (high confidence) (IPCC, 2022)-(IPCC AR6) (IPCC, 20221). The potential of more destructive TC events will require updating

220 and enhancement of existing risk reduction strategy. The Sendai Framework for Disaster Risk Reduction provides a structure for reducing disaster damages and increasing resilience to hazards including TCs (Bennett, 2020). One mechanism they encourage in Goals 18 and 24 is the distribution of multi-hazard risk information such as risk assessments.

Risk assessments combine hazard information with human activity, infrastructure and natural

- 225 resources to determine the possible impacts of hazardous events (Belluck et al., 2006; National Research Council, 1991) and make informed choices for risk management in the most exposed and vulnerable regions (Aguirre-Ayerbe et al., 2018). Disaster risk is defined as the probability of harmful consequences, or significant losses, resulting from interactions between a hazard, and the local exposure and vulnerability to that hazard (Crichton, 1999; Downing, 2001).
- 230 As Local Government Areas (LGAs) are the one of the smallest government decision-making bodies with available census datay, information is sought to be provided on that scale. Risk assessments are a foundation for early warning systems to raise alerts of potential impacts, and to provide evidence for the prioritisation of funds and resources to areas in advance of any hazardous events. While the climate continues to change alongside evolving human activity, risk assessments must likewise be
- regularly updated to stay accurate and useful as a tool for disaster risk reduction (Peduzzi et al., 2012).

For TCs, the four main hazards are the destructive winds, associated storm surge, flooding from associated heavy rainfall, and landslides on steep terrain as soils saturate (Murray et al., 2020). TCs and other natural hazards are becoming increasingly recognised as multi-hazardous in nature (Scawthorn et al., 2006)-(Scawthorn et al., 2006a). These hazards impact regions differently and their effects can compound to cause even greater damage (Gori et al., 2020).

While TCs can cause damage through different hazards, such as gale-force winds, storm surge or flooding, the communication of TC intensity and categorisation places emphasis on wind speed (Lavender and Mcbride, 2020). This is partially due to the availability of wind measuring technology and the relative ease to quantify wind. Publicly available warnings and forecasts are focusing on wind speeds, ultimately portraying the message that winds are the hazard to be most wary of. The literature however suggests the <u>TC-induced</u> impacts of storm surge and flooding contribute to the most human lives lost and infrastructure damage (Mendelsohn et al., 2012; Zhang et al., 2008).

Although some studies have included multi-hazard aspects of TCs_(Burston et al., 2017) (Burston et al., 2017b),-presenting different hazard models for <u>TC-induced</u> storm surge, wind and flooding, these studies do not complete the story of combining hazard with exposure and vulnerability to map risk. Similarly, within the literature, there are many examples of standalone exposure or vulnerability index assessments for TCs (Marín-Monroy et al., 2020; Bathi and Das, 2016; Amadio et al., 2019). This gap indicates compelling scope to develop a multi-hazard TC risk assessment that can

255 differentiate the extent and severity of TC-related-<u>induced</u> hazards.

This study will address this gap and strengthen TC risk information for the Australian region. Multihazard risk is assessed and visualised through-interactive maps which show LGA categorisation, alongside hazard, exposure, and vulnerability layers. As a risk assessment's usefulness relies on how they are tailored for a specific users audience or applications, the method proposed in this study serves as a proof of concept that can be altered in future iterations for tailored use.-





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Figure 1. Map of study area, state, and territory boundaries as well as Local Government Area (LGA) divisions and major cities. States and territories: Western Australia (WA), Northern

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265 Territory (NT), Queensland (QLD), South Australia (SA), New South Wales (NSW), Australian Capital Territory (ACT), Victoria (VIC) and Tasmania (TAS) are labelled.

Table 1. Comparison table of each Australian states general characteristics including total area, real GSP and population (Australian Bureau of Statistics, 2020-2021)

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STATE	TOTAL AREA	Number	Avg. area per	<u>GSP</u>	Population	GSP per
		<u>ot lgas</u>	LGA	<u>(Şmillion)</u>		capita (Ş)
Australia Capital	2358	<u>1</u>	2358.172	433740	431483	100523
Territory (ACT)						
New South Wales	<u>800811</u>	<u>130</u>	<u>6160.083</u>	<u>6336350</u>	<u>8172561</u>	77532
<u>(NSW)</u>						
Northern Territory	1348094	<u>18</u>	74894.13	261810	246565	106183
<u>(NT)</u>						
Queensland (QLD)	1730172	<u>78</u>	22181.69	3689770	5194884	71027
South Australia	<u>984275</u>	<u>71</u>	<u>13863.03</u>	1149210	1770794	<u>64898</u>
<u>(SA)</u>						
<u>Tasmania (TAS)</u>	68018	<u>29</u>	2345.443	340830	541499	62942
Victoria (VIC)	227496	80	2843.695	4682640	6661697	70292
Western Australia	2526646	<u>137</u>	18442.67	3206530	2670231	120084
<u>(WA)</u>						

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Australia is a country with a long coastline and with much of its northern states commonly impacted by tropical cyclonesTCs. An average of 12 TCs form in the Australian region annually (however, interannual variability is high ranging from 19 TCs in 1983/84 to 3 TCs in 2015/16, for records examined from 1970/71 to 2019/20 TC seasons (Kuleshov et al., 2020)), with 5 making landfall on average (Mortlock et al., 2018). In the last few decades, several severe TC events have destroyed 275 infrastructure and caused billions of dollars in losses, including TC Larry (2006), TC Yasi (2011) and TC Debbie (2017).

Figure 1 shows the boundaries of each state and territory as well as the outline of Local Government Area (LGA) divisions within. Table 1 summarises key traits of each state such as their total area, real Gross State Product (GSP) and population. From the Ttable 1 it can be seen that NSW and VIC are the states with the highest GSP (monetary measure of state output), as well as highest populations. For TC-related impacts however, we are most concerned with interested in the northern states that are expected to more commonly be impacted by TC events. QLD and WA therefore stand out as the next most important states with next highest GSP and populations. Important to note however is the size of QLD and WA states and much higher average area per LGA, meaning GSP contribution and populations are likely to be much more spread out.

2.3. Data and Methodology

To calculate the multi-hazard risk of TCs to Australia, hazard, exposure exposure, and vulnerability datasets were chosen and sourced. This data was then joined combined to LGA map shapefiles in ArcGIS Pro. To calculate exposure and vulnerability indexes from multiple indicators, equal weighting was used for exposure, while Pareto front-ranking was used for vulnerability. Combined with hazard values for each LGA, exposure and vulnerability indexes were used to calculate risk using equation 1:

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Risk = Hazard x Exposure x Vulnerability

<u>(1)</u>.

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1.1.-3.1 Selection of indicators

Table 2. Dat	ta table for LGA risk analysis. Lin	ks are provided for the data	sources as well	as •	Formatted: Normal, No bullets or numbering
<u>the year that the ua</u>	llaset was last upualeu.				
Indicator	Dataset used	Source	<u>Year</u>	Data forma and resolution	<u>t</u>
<u>Hazard</u>					
Surge hazard	<u>Global tropical cyclone storm</u> <u>surge run-up height, 100yr</u> <u>return period</u>	<u>GAR Atlas</u> (2015)	2015	Point data (every 1km along coastline)	Field Code Changed
Flood hazard	Australian flood depth	GAR Atlas	2015	Raster data	Formatted: Not Highlight
	inundation, 100yr return	(Rudari et al., 2015)		<u>(1km)</u>	Formatted: Not Highlight
Wind hazard	Australian tropical cyclone wind, 100yr return period	<u>Geoscience Australia</u> (Arthur, 2018)	<u>2018</u>	<u>Raster data</u> (2km)	
Landslide hazard	Global landslides hazard	<u>ThinkHazard!</u> (Arup, 2020)	2020	<u>Raster data</u> (1km)	
LGA Exposure					
Population	<u>Recorded total number of</u> people living in each LGA.	ABS Census data	<u>2016</u>	<u>Tabular data</u> (LGA resolution)	<u>à</u>
Public hospital	Point feature layer of public hospitals around Australia	ArcGIS Online Dataset	2019	<u>Point data</u>	
<u>Substations</u>	Point feature layer of power substations around Australia	Geoscience Australia	2016	<u>Point data</u>	
<u>Powerlines</u>	Line feature layer of powerlines around Australia	Geoscience Australia	2016	<u>Line data</u>	
LGA Vulnerability					
IRSD	<u>Summary statistic for</u> socioeconomic status,	ABS Census data	<u>2016</u>	<u>Tabular data</u> (LGA resolution)	<u>à</u>

No vehicle homes	Percentage of households within each LGA that owns zero vehicles.	ABS Census data	<u>2016</u>	<u>Tabular data</u> (LGA <u>resolution)</u>
Vulnerable age groups	<u>Percentage of LGA</u> population that is under 15 or over 65	ABS Census data	<u>2016</u>	<u>Tabular data</u> (LGA resolution)
Shape layers				
LGA polygon layer	Shapefile containing the size of each LGA as of 2016	ABS Australian Statistical Geography Standard	<u>2016</u>	<u>Polygon</u> <u>data (LGA</u> <u>resolution)</u>

Hazard

The main identified hazards of TCs include storm surge, winds, landslides, and floods. The 100 year100-year return period was chosen to represent the current long-term probability-danger of these hazards occurring, in the near future. Of note is that these probabilities may change in the future with studies predicting increased storm surge levels (high confidence) and increased TCrelated precipitation (medium-high confidence) due to climate change (Cha et al., 2020).

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Storm surge data was acquired from GAR Atlas' risk and data platform, which mapped TC storm surge height as point data roughly along the Australian coastline every 1km. TC wind data was sourced from Arthur (2018) and came as high-resolution raster data over Australia and its northern waters. Flood data was sourced from Rudari et al. (2015) as high-resolution raster data representing riverine flooding only. Thus, non-null values tended to only appear near riverine systems and catchments. Similarly, landslide data from Arup (2020) was in the raster format with mostly null 310 values apart from specific locations with significant landslide hazard.

Storm {Arthur, 2018 #181@@author-year}and wind datasets were specifically designed for TCs (Cardona et al., 2014; Arthur, 2021)surge and wind, and spatial mean values were calculated over each LGA. For flood and landslide hazards the original datasets did not consider solely TC induced floods/landslides. Thus, the flood and landslide hazards were weighted towards TC prone regions by multiplying values by the TC wind raster dataset. Weighted flood and landslide values were then summed over LGAs as there were many null values. Greater than zero values exist only around water catchments and rivers for floods, and around mountain regions for landslides. Thus, LGAs with higher flood and landslide values have more of these prone environments in total rather than a higher areal proportion.

320 Exposure

Exposure indicators of population, hospitals, substations, and power lines were chosen to represent physical assets of human life, as well as systems and infrastructure that are important in the case of emergency disaster events (hospitals, power). Failure to maintain the function of lifeline infrastructures such as hospitals and power can lead to exacerbated negative impacts (Ju et al., 2019). These chosen indicators aim to spatially describe which LGA regions have more exposed

assets relative to the rest of the country. Electrical substations provide power as critical infrastructure and are strategically placed to meet demand. Similar reasoning influenced the choice of public hospitals and powerlines.

While population density data of each LGA was found in tabular form from the Australian Bureau of
 Statistics (ABS), the remaining exposure indicators' raw format was as point or line shapefiles
 displayable in ArcGIS Pro. Thus geoprocessing tools such as spatial join were used to count the
 number of public hospitals in each LGA. Using absolute measurements can be inappropriate when
 considering regions of different sizes (Rygel et al., 2006), thus these counts were then divided by LGA
 area to give a density value similar to that of population density.

335 Vulnerability

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Vulnerability indicators were chosen to represent regions most susceptible to high impact from a TC event occurring in the vicinity. Measures of socioeconomic status are commonly used to describe vulnerability to natural hazard events (Mitsova et al., 2018; Lianxiao and Morimoto, 2019) and the Index of Relative Socioeconomic Disadvantage (IRSD) has been used in earlier studies previous 340 literature for the Australian region (Rolfe et al., 2020). It summarises variables about the social and economic conditions of households. The more disadvantaged a region is socioeconomically, the more likely it will be more impacted by TCs, due to factors such as lower income, having families with only one parent or having a higher percentage of people that have English as a second language. The 'no vehicle homes' indicator was derived by calculating the percentage of homes with 345 no vehicles, and the 'vulnerable age groups' indicator was constructed by calculating the percentage of an LGA's population made up of the <15 and >65 age group combined. The 'no vehicle homes' indicator is considered as particularly relevant to TCs as it provides information on LGAs that are more susceptible to loss of human life in evacuation situations. Although this risk assessment highly values human life and safety, historically within Australia, TCs have caused very few fatalities in 350 recent decades, and an indicator describing the vulnerability of infrastructure would be preferred. An alternative to 'no vehicle homes' vulnerability indicator could be the proportion of houses that are not constructed to modern wind loading standards. While this potentially useful indicator was not included in this study due to limited data availability, this could be a topic for future work.

355 Vulnerability indicators are ideally directly linked to their relevant exposed counterparts; however,
 355 these human and society-centred vulnerability indicators were chosen to generally relate to selected
 achosen exposure indicators which can be estimated as populations and the built environment they
 are surrounded by. Direct infrastructural vulnerability indicators were of interest, such as building
 code standards to give information on their susceptibility to wind damages, however due to limited
 data and the multi-hazard approach of this study, a more general approach was taken.

360 The data that was used to create the risk maps are summarised in Appendix 1.

1.2. 3.2 TC Risk Mapping Mapping Process

The TC risk mapping process is schematically described in Figure 1. Before risk could be calculated and mapped based on the collected datasets, data was transformed and converted, as described in the diagram. Most processes occurred within ArcGIS Pro software, however, Python scripts were also utilised for some calculations. First, acquired indicator data was transformed and converted into

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the LGA resolution. As raw data came in tabular (a), point (b) and raster (c) formats, different methods for each were used to summarise information when converted to LGA polygons (d) as depicted in Figure 2. Tabular data from the ABS came at an LGA resolution, so data only needed to be linked to an LGA polygon shapefile in ArcGIS Pro. For storm surge point data which spanned across the coastline every 1km, the average 100-yr surge height value was taken, whereas for exposure point data such as hospitals and substations, the count or number of points in each LGA was taken. For the wind raster data which had no null values and gradually changed in value inland, the mean windspeed value was taken per LGA, while with flood and landslide data the sum of nonnull values was taken per LGA.



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Figure 2. Diagram representing data formats of acquired raw data (tabular (a), point (b), raster (c)) being transformed into a comparable LGA polygon format (d). (Example data is used here, and (d) is not representative of any results)

Once in a comparable data format, indicator data values were normalised into a 0 to 1 range with decile normalisation against the whole country using Python scripts. Use of different normalisation methods were tested, such as linear normalisation and natural breaks, however decile normalisation was found to best remove the skewing effects of outliers, and is a method commonly used in several ABS indices.

Figure 3 depicts the different tiers or stages of the risk assessment, starting at tier (3) with the
 indicators. These are the variables that differ in value spatially across Australian LGAs, that were
 chosen to be representative of TC hazard, exposure, or vulnerability. Three to four indicators were
 chosen to give a more robust index without diluting the sensitivity of each indicator. From tier (3) to
 tier (2), or from indicators to indices, different methods were used depending on the index. For
 explained in the next-sub-section (3.3). With only one indicator or dataset for each hazard of TCs,
 each hazard was passed through separately, meaning when hazard, exposure, and vulnerability
 indices were multiplied as outlined inusing equation 1 to calculate risk (tier (2) to tier (1)), four

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Creating the exposure index by equal weighting (averaging) decile values Formatted: Left, Space After: 10 pt of the four exposure indicators 415 Formatted: Left Creating the vulnerability index by using Pareto Front ranking on the three vulnerability indicators $\overline{\mathbf{v}}$ Creating the risk index for each hazard by multiplying decile hazard values, the exposure index, and the vulnerability index for each LGA 420 \mathbf{V} Creating map layers for each hazard, each indicator and each index, colour coding Formatted: Left, Space After: 10 pt Formatted: Left Creating a final TC risk layer by equally weighting the risk of each hazard 425

Figure 1.TC risk mapping process.

2.3. 3.3 Indices Calculation

First, for processing raw indicator data, decile and natural breaks transformations were explored.

Decile ranking in this context compares the values of each LGA to the LGAs in the rest of the country. 430 A value of 0.9 would indicate the LGA has a value larger than 90% of LGAs in Australia, and every 0.1 interval would hold 10% of LGAs. In this way, all indicators can effectively have an impact on resultant indices and risk maps even with the presence of outliers, which will take decile values on either end of the spectrum without causing any skew. Decile ranking is used in indices such as Socio-Economic Indexes for Areas (SEIFA) from which IRSD is a part of, to give relative meaning to the raw scores.

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Natural breaks can similarly address the limitations of 0 to 1 normalisation by using optimisation to categorise values and minimise the amount of variance within each category. The number of categories can be increased automatically until a threshold of variance is met (96% in our case, as 97% required more than 20 categories). The breaks or classes chosen depends on and is unique to every distribution or set of data. Additionally, the number of classes is not fixed, which can result in

440 fewer unique values and less value variation between LGAs, which is less informative.

Based on these considerations, decile ranking was chosen as the method of processing raw indicator data. Natural breaks however were used in the presentation of final index and risk maps and colour classes as it is the standard in geographical mapping for choropleth maps (Anchang et al., 2016),

445 providing a quick overview and differentiating values more clearly than a continuous scale-clusters of values to easily recognise trends.

Second, index calculations were performed. Equal weighting is commonly used to create index values from a set of indicators, and is used either for simplicity or because there is no supporting evidence to suggest how different indicators should be weighted (Rygel et al., 2006). In the context

of TCs in Australianatural hazard risk assessment, while past studies have suggested that a weighted framework could improve results (Do and Kuleshov, 2022), butit would require more research - such as gathering expert opinion and conducting detailed sensitivity analyses -- to weigh chosen indicators (Amadio et al., 2019). One of the limitations of equal weighting is that very high values in one indicator are averaged with other indicators in the index, resulting in a potentially lower value that does not capture the extreme aspect of that LGA. This is particularly a problem for the vulnerability index because a region only needs to be extremely vulnerable in one factor to be

considerably more at risk (Rygel et al., 2006).

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Pareto ranking, also known as Pareto front optimisation or multi-objective optimisation, was investigated to address some of the limitations of the equal weighting method. Pareto ranking can be used to construct an effective vulnerability index without weighting individual indicators (Huang et al., 2013; Nelson et al., 2020). It involves finding the values along the Pareto front, which are values considered to be non-dominated in all indicator axes and ranking these fronts in order. The process is depicted in Figure 42 which shows a step-by-step process of identifying non-dominated data points.



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Figure 42. Graphic demonstration of Pareto front classification in two dimensions. <u>A non-dominated</u> <u>point is one that has no other points above and to the right of it.</u> The same principle applies when scaled to N number of dimensions. Adapted from Rygel et al. (2016)

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First data is plotted along axes representing each component/indicator. Each data point in this study would represent an Australian LGA. Then the first non-dominated front would be identified as the set of points that do not have any LGAs with both a higher value in indicator 1 orand indicator 2. This

first front would be ranked highest and set aside, with the same methodology being <u>repeatedly</u> used to identify subsequent fronts <u>using the remaining data</u>. In the case of the example in Figure <u>4</u>2, with 4 distinct fronts or classes, an index value would be given at even intervals (e.g. 0.2, 0.4, 0.6, and 0.8) with LGAs sharing the same index value as LGAs also in their front.

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The Pareto ranking method, therefore, can identify LGAs as vulnerable due to one or two indicator values even if its other indicator values are lower. Although vulnerability benefits from Pareto ranking as the maximum magnitude across all indicators is the defining factor, the exposure index benefits from taking into account all indicators cumulatively assuming the selected indicators are relevant. Thus Pareto ranking was used to calculate the vulnerability index in this study, while equal weighting was chosen for the exposure index.

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2. <u>4.</u> Results and Discussion

The <u>TC</u> hazard, exposure, vulnerability, and risk maps are presented and discussed in this section.

2.1. <u>4.1</u> Exposure

The exposure index was created from equally weighting the four indicators: population density, hospital density, electrical substation density and powerline length density. In Figure 53, it can be seen that population density is highest along the eastern coast and surrounding major cities, especially in New South Wales (NSW)NSW and Victoria (VIC) VIC. The hospital density indicator shows very similar patterns although there are fewer LGAs with the lowest exposure classification.
Substation and powerline indicators both have similar patterns to each other with the highest exposure along south-western Australia (WAWA), southern South Australia (SA) SA, most of VIC, and eastern NSW and Queensland (QLD) QLD. The calculated exposure index in Figure 64 maintains the clear trends of highest exposure along the country's eastern coast, and around major cities. Also of note areExceptions include moderate to high-relatively high exposure values around the Pilbara region in north-western WA (Karratha, Ashburton, Port Hedland, East Pilbara LGAs) and around Townsville further up the QLD coastline.the Mount Isa LGA in western QLD.





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Figure 53. Exposure indicator maps of population, hospital, substation, and powerline density.



505 **Figure 64.** Exposure index map created by equally weighting four exposure indicators.

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Exposure maps largely reflect the disproportionate percentage of Australia's population that lives on the coast (Abuodha and Woodroffe, 2006) and near major coastal cities. As infrastructure such as public hospitals and substations are positioned to meet demand, it is also understandable why similar patterns are found amongst chosen indicators.

Aside from these highly populated and built-up coastal regions <u>near major cities</u>, relatively higher exposure index values were identified around the Pilbara and <u>Mount Isa regionsTownsville regions</u>. The mining industry's presence in regional Australia is most obvious within the Pilbara region of north-west WA<u>, with and the Mount Isa region of north-west QLD</u>. There are a large number of many fly in fly out workers for these regions, and they which make a significant contribution to

515 of <u>many</u> fly-in-fly-out workers for these regions<u>, and they which</u> make a significant contribution to the economy. Although none of the chosen indicators were mining industry-related, the population

and substation densities infrastructure indicators were able to indicate detect significant exposure in those areas related to the mining sector. High exposure of Townsville can be explained by a high population making it the largest settlement in North QLD, along with moderate infrastructure indicator values. The city is a popular tourist destination being adjacent to the Great Barrier Reef and national parks, while also hosting large metal refineries.

From the calculated exposure maps, we can see that assets possibly lost in a tropical cycloneTC event are highest along the country's eastern coastline as well as surrounding major cities. Thus we would expect the potential for highest risk in these regions if vulnerability and hazard are also high.

2.2. <u>4.2</u> Vulnerability

The vulnerability index was created by Pareto ranking the three indicators: IRSD, vulnerable age groups and no vehicle homes.

Figure 75 shows that IRSD vulnerability is extremely high across most of central and western Australia, with the highest class values across almost all of NT. Otherwise, vulnerability is 530 considerably lower in the LGAs surrounding the major cities in each state. Conversely, the vulnerable age indicator shows the lowest values across central and western Australia. Although inner cities also show low vulnerable age values, the highest values are found in outer suburban LGAs. For no vehicle homes, central and north-western Australia have the highest vulnerability values, with lower values near and surrounding major cities. The calculated vulnerability index in Figure 26 shows low to medium vulnerability values in LGAs surrounding cities, with higher vulnerability regions across NT, northern QLD, and northern NSW to northern VIC.

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0.61 - 0.80

0.81 - 0.90



Figure 75. Vulnerability indicator maps of IRSD, vulnerable age groups and no vehicle homes.



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Figure <u>86</u>. Vulnerability index maps calculated by Pareto ranking three vulnerability indicators.

IRSD patterns show lower vulnerability in major cities, as they are most developed and relatively affluent. High vulnerable age group values outside of and surrounding major cities can be explained by the >65 age group retiring and relocating out of urban areas (Vintila, 2001). Of the 16 IRSD input variables, 'NOCAR', was described as the percentage of occupied private dwellings with no car.

Although it is not certain whether this variable is the same as the no vehicle homes indicator used in this study from the Number of Motor Vehicles census record, some overlap is to be expected. This means regions with high no vehicle home vulnerability values are likely to have their vulnerability index overestimated. The fact that NOCAR is only one of 16 variables in the IRSD also suggests similarities between the two indicators may be from correlation in other variables instead.

- 555 Compared to the exposure index, the transition from patterns in the indicator maps to the vulnerability index are not as clear, as Pareto ranking is used instead of equal weighting. Pareto ranking was used to address situations where a high value in one indicator would be overlooked after being equally weighted with indicators with medium to low values. Instead, it ranks LGAs on the higher end if a single indicator's value causes it to be non-dominated much earlier. However, our
- 560 analysis showed that having one indicator with the highest classification value does not guarantee a high vulnerability index value. In fact, having two indicators with the highest classification values does not guarantee a high value either as can be seen across central and north WA. This is partly because within each coloured class, there is a range of values, and only the highest values are picked out by Pareto ranking as non-dominated. This suggests the second highest class of values in the vulnerability index (2nd darkest purple) are also important and possibly underestimated.

This idea of there being a lot of competition at the higher value range within indicators is highlighted by the case of the Maralinga Tjarutja LGA in western SA, which is in the highest vulnerability index class. The LGA does not have a recorded IRSD value from the ABS, meaning the region isn't competing for a non-dominated spot on the IRSD axes. This allows the LGA to receive a very high

570 vulnerability index score from only a very high vulnerability value in the no vehicle home indicator alone.

Overall, the vulnerability index shows higher vulnerability and thus predicts higher risk throughout NSW, northern QLD and northern NT.

2.3. 4.3 TC Hazards

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<u>TC h</u>Hazard maps were created from datasets of chosen hazards of storm surge, flooding, wind, and landslides as shown in Figure 97. Ten quantile classes (decile) were used to present these <u>TC hazard</u> maps to represent values and display any trends more precisely.

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Figure 97. Hazard maps of storm surge, flood, wind and landslides associated with Tropical Cyclones.

- Surge heights are seen to be highest <u>along a long portion of</u> north-western WA₂ and surrounding Darwin, <u>and at a few locations along QLD's eastern coastline</u>, having 100-year return period surge heights greater than <u>2</u>3m. Surge hazard is otherwise lower around other parts of the country's northern shoreline and has values of 0 in LGAs not bordering the coastline. Flood hazard is shown to have the highest values across northern <u>LGAsWA</u>, <u>NT and most of QLD</u>, with <u>mediumsignificant</u>
 values <u>over much of QLDreaching into NSW</u>. Wind hazard is more consistent, with TC wind speeds highest in coastal LGAs, with hazard decreasing towards the centre of Australia and further south. Landslide hazard is highest in northern WA <u>and NT</u> along with <u>medium-high</u> values <u>throughout</u> throughout NT and along the Great Dividing Range along the eastern coast of the countryeastern <u>QLD and north eastern NSW</u>.
- While it would be expected that the multiple hazards associated with TCs follow the general location
 TCs more commonly make landfall, there are clear differences between hazard maps in Figure 97. This shows how the physical characteristics of each LGA can change the intensity with which
 different TC hazards impact different regions. For example, flood and landslide hazards have the potential to affect more inland regions while storm surge is only relevant for coastal LGAs, and wind
 more uniformly decreases south and inland. These results emphasise the importance of considering the multi-hazard nature of TCs and mapping their differing extents.

The storm surge hazard map shows greater than zero values only for coastal LGAs, however, a few LGAs may raise concern. The first is East Pilbara, the large LGA in WA with very high surge values. Although most of the LGA is quite far inland and would not be affected by potential storm surge, the
 LGA does border the coastline in its northwest corner. Due to input surge datasets having the format of point data dotted every few kilometres along Australia's coastline and chosen methods averaging intersecting surge point data to each LGA polygon, East Pilbara was mapped with very high surge hazard. For a similar reason of input hazard data only dotting the main coastlandmainland, some island LGAs were left without a surge value and thus mapped with very lowlowest hazard. For
 example, Tiwi Islands north of Darwin, and Mornington Island in north-western QLD. Considering their location and the hazard values of neighbouring LGAs, these island LGAs in the country's north potentially have medium to very high hazard values rather than none at all. These cases pose the question of the chosen LGA resolution in this study, with higher resolutions being preferred

1	especially for hazard indicators. The method in this study however applies the same rules and
615	calculations for all LGAs, which allows for a low resource and quick rendition of relative hazard.
	Wind hazard trends are to be expected and are consistent with TC genesis and development theory
	where TCs start to they lose intensity after landfalling, having its energy source of warm ocean water
	cut off. and being cut off energy source while as they penetrate inland, no longer being supported
	with convection currents from over ocean. Additionally, as they move away from the tropics too far
620	from the equator, TC's storm structure can weakens and collapse, sometimes continuing to exist as
	an ex-TC storm and they transition into extra-tropical systems with less organised convection and
	lower wind speeds, although still capable of continuing to to to bringing heavy precipitation if the
	conditions allow. This could partly explain why surge and wind, which rely on high wind speeds,
	affects less regions strongly south of QLD than flood and landslide hazards which rely on heavy and
625	sustained precipitation.

An important consideration when evaluating flood and landslide hazards is that a cumulative method was used to calculate hazard values from input datasets. Rather than taking averages over each LGA as was done for surge and wind, flood and landslide input datasets were high-resolution raster maps with many null values. Using an averaging methodology would have described an LGA's hazard in proportion to its area, meaning larger LGAs with many flood-prone regions could still have a low flood hazard value. Instead, values were summed, meaning greater than zero hazard values meant a region had some hazard-prone regions, and high hazard values meant they had more regions prone to flooding/landslides regardless of the LGA's size. While this does mean larger LGAs have the potential to reach higher hazard values, this method represents all possible hazards, and

therefore risk, rather than underestimating it due to averaging methods.

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2.4. 4.4 TC Multi-hazard Risk

Risk maps were created by multiplying each hazard with the exposure and vulnerability indices. This produced the four hazard-specific risk maps in Figure <u>10</u>%, from which a total TC risk map was created by equally weighting them as seen in Figure <u>11-9</u>. A Natural Breaks symbology was used for these risk maps to group similar values and maximise variance between groups for a visually informative map.

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Figure <u>10</u>8. Risk maps for each hazard (surge, flood, wind, landslide).



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Figure 119. Combined multi-hazard risk calculated by equally weighting four hazard-specific risk maps.

Surge risk is considerable along the northern, western, and eastern coasts, with the highest values between Brisbane and Cairns in QLD. Flood risk can be seen to be highest across both NSW and QLD 650 with medium values along the top of NT and WA. Risk to the wind is very uncommon at distances greater than 500 km inland and south of NSW, with the highest wind risk found along with the eastern parts of NSW and QLD. Landslide risk also shows the highest risk in eastern NSW and QLD with medium risk across northern NT. The combined TC risk map displays some of these more prominent patterns from each hazard-specific risk map. For example, eastern NSW and QLD have the highest risk followed by medium risk across northern WA and NT. The risk to TCs is very low

inland of the country surrounding SA, as well as south of NSW, in VIC-and Tasmania (TAS) states and TAS.

As patterns seen in risk maps can be partially explained by similar patterns found in constituent layers, it is important to compare them to hazard, exposure and vulnerability layers. While an overall 660 TC risk map is useful for such discussions, hazard-specific risks are important to consider and compare at a local level, for example when LGA councils are planning disaster management strategies or communicating warnings to residents for an incoming TC. Of note is that although TCs generally form over tropical warm waters and affect regions near the tropics, they intensify away from the equator reaching maximum intensity approximately at 17-18°S 665 of the equator (Kuleshov, 2020), which partially explains why risk is not highest in all northernmost LGAs. Another contributing factor to medium risk values in the country's north is due to there being relatively fewer assets exposed compared to the rest of the country, as shown by the exposure index in Figure 64. Continuing moving further south away from the tropics, TCs are weakening as sea surface temperatures get colder in extra-tropical regions. Hence, substantial reduction of risk is 670 observed in VIC and TAS. Similarly, TCs weaken over land which is why risk is also very low for central Australian LGAs. The lower risk in these states is supported by historical records of TC tracks from 1970-present (Kuleshov, 2020). From the overall TC risk map in Figure 9, QLD and NSW have the most LGAs with very high-risk 675 scores, particularly along the eastern coast. This result can partially be attributed to high hazard values, as well as high exposure index values with many people and infrastructure built up around those regions. Of note is that although TCs generally form over tropical waters and affect regions near the tropics, they intensify away from the equator reaching maximum intensity approximately 17-18°S of the equator (Kuleshov, 2020), which partially explains why risk is not highest in all 680 northernmost LGAs. Another contributing factor to medium risk values in the country's north is due to there being relatively fewer assets exposed compared to the rest of the country, as shown by the exposure index in Figure 4. Continuing moving further south away from the tropics, TCs are weakening as sea surface temperatures get colder in extra-tropical regions. Hence, substantial reduction of risk is observed in VIC and TAS. Similarly, TCs weaken over land which is why risk is also very low for central Australian LGAs. The lower risk in these states is supported by historical records 685 of TC tracks from 1970 present (Kuleshov, 2020). The risk maps in Figures 10 and 11 attempt to compare the relative risk of each LGA in Australia by summarising values of relevant hazard, exposure, and vulnerability indicators. Thus, we can investigate the risk in a certain region, and trace it back to its components' trends which should show a similar story. The highest risk regions 690 identified along the eastern half of NSW and QLD in all risk maps (exclusively along the coast for surge risk) represents the dense heavy distribution of populations and infrastructure along Australia's eastern states as seen in exposure maps in Figures 5 and 6. Accompanied by very high flood and landslide values, with wind and storm surge weakening in the southern half of NSW, the eastern strip of Australia stands out to have the highest risk. The influence of vulnerability has a less 695 noticeable trend as it does not uniformly compound in all regions with high hazard and exposure, but can be seen to increase risk particularly in north-central NT, northern QLD and northern NSW. This holistic approach to assessing risk is helpful in understanding the possible impacts if a TC was were to occur and affect any region in the country. Results have shown that this methodology is effective in visually describing and identifying regions with high risk component values, and hopes to 700 provide relevant risk information to assist disaster management and resilience decision makers.

2.5. 4.5 Limitations of Risk Assessment

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One of the limitations of this TC risk assessment of Australian LGAs is that indicators were selected partially because of data availability, and hence may not represent all aspects of hazard, exposure, or vulnerability. For example, within the vulnerability index, indicators that informed a region's preparedness to natural disaster events were not available. While some LGA councils may have informative documents or evacuation plans, it is difficult to determine how well understood they are by residents, and the data is not standardised in the format that can be compared against LGAs across the country. Additionally, in some cases lower resolution global hazard datasets were used because they were available, while higher resolution, Australia-specific datasets are yet to been

created or were inaccessible.

Being a risk assessment, subjective indicator choices were made which can shift how results should be interpreted (Aguirre-Ayerbe et al., 2018; Brooks, 2003). For example, chosen exposure indicators identified regions where many lives were exposed alongside physical lifeline infrastructure that

715 contributes to health and utilities (hospitals, powerlineselectricity). These indicators however do not accurately address potential financial losses if businesses and industries were not able to function due to TC damage. As a result, discussion of risk map implications would need to stay human-centric. While just adding more indicators could be identified as a possible solution, the nature of risk and index calculations mean that adding more indicators reduces the importance of each, resulting in a 720

potentially less informative final risk map.

Another limitation is that while each indicator map had patterns identified, the discussion was based on an incomplete understanding of Australian LGAs. Ideally, formal validation of each indicator with local knowledge from people who reside in or manage each LGA would ensure that each contributing input to end risk maps were accurately represented. This would be particularly important for TC hazard data as exposure and vulnerability indicators from the ABS are typically well.

725 validated and iterated upon every census. Engagement with indigenous people would also be an essential aspect of validation so that cultural assets and indigenous knowledge are included in the maps.

3. 5. Conclusions

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The developed novel methodology for multi-hazard TC risk assessment and created maps showed the differences in hazard extent and differing characteristics of each region that made an LGA at risk to TCs. Generally, the highest level for all TC hazards was found along the eastern, northern, and western, coasts, with all TC hazards being weakest far inland and in the southern parts of the country. Selected exposure indicators represented human lives as the most important asset at risk, which was found to be highest around major coastal cities in each state, while vulnerability showed 735 more varied spatial trends. Final TC risk maps suggested most at-risk states were QLD and NSW for all TC hazards, particularly in the states' eastern regions followed by medium risk across Northern Territory and north-west of Western Australia-. As with all risk assessments, the selected indicators should be considered before using resultant maps to inform decisions, and future work includes all-740 important validation studies.

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5. Appendix

Appendix 1. Data table for LGA risk analysis. Links are provided for the data sources as well as the year that the dataset was last updated.

Indicator	Dataset used	Source	Year
Hazard			
Surge hazard	Point feature layer of Storm surge run-up height, 100yr return period	GAR Atlas	2015
Flood hazard	Raster Flood depth inundation, 100yr return period	<u>GAR Atlas</u>	2015
Wind hazard	Raster Cyclone wind, 100yr return period	Geosciences Australia	2018
Landslide hazard	Raster Global landslides hazard	ARUP	2020
LGA Exposure			
Population density	-Recorded total number of people living in each LGA.	<u>ABS Census data</u>	2016
Public hospital	-Point feature layer of public hospitals around Australia	-ArcGIS Online Dataset	-2019
Substations	-Point feature layer of power substations around Australia	- <u>Geosciences Australia</u>	-2016
Powerlines	Line feature layer of powerlines around Australia	- <u>Geosciences Australia</u>	-2016
LGA Vulnerability			
IRSD	-Summary statistic for socioeconomic status,	ABS Census data	2016
No vehicle homes	-Percentage of households within each LGA that owns zero vehicles.	ABS Census data	2016
Vulnerable age groups	Percentage of LGA population that is under 15 or over 65	ABS Census data	2016
Shape layers			

LGA polygon layer Shapefile containing the size of each LGA as of 2016		
	LGA polygon layerShapefile containing the size of each LGA as of 2016ABS2016	