Science interrupted: tropical cyclone forecasting developments in the Deep South National Science Challenge

Article

Science interrupted: Tropical cyclone forecasting developments in the Deep South National Science Challenge

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In this article I describe the state of understanding at the end of the Deep South National Science Challenge concerning how tropical cyclones – TCs, such as 2023's Gabrielle – may change in the future. TCs are some of the most destructive weather systems on Earth, and understanding how they may change in the future is of enormous societal and economic concern. A state-of-the-art climate model is used, forced with several future climate scenarios to study TCs affecting the New Zealand region. UKESM1 is a coupled atmosphere-ocean earth system model and the TCs predicted by it are found using offline software which tracks the position of simulated pressure lows through time. The software used is validated against the tracks of cyclones from 1968 [Giselle] and 2023 [Gabrielle] as well as a different cyclone tracking software package. The power dissipation index, PDI, gives a first order measure of TC strength and it is found that the average PDI per storm increases with top-of atmosphere radiative forcing by up to 24% under a 'fossil-fuelled development' scenario, SSP5-8.5. I conclude with a discussion on New Zealand's future research landscape.

Introduction

Funding and research landscape

The Deep South National Science Challenge ran for ten years up to July 2024 and had the overarching mission of being able to 'anticipate, adapt, manage risk and thrive in a changing climate.'

The Earth System Modelling (ESM) programme within the Challenge developed the New Zealand Earth System Model – NZESM – which is a variant of the global UK Earth System Model with an embedded high-resolution ocean included around New Zealand and the Southwest Pacific. Several studies using the NZESM have been published in respected peer-reviewed journals. These studies include the study of improved representation of ocean circulation in the New Zealand Region (Behrens et al., 2020) and improving the ability of Kiwi scientists to understand future marine heatwaves; periods of extended high temperatures and ocean heat content in a region which 'host[s] a rich and diverse marine ecosystem, aquaculture facilities and commercial and recreational fishing grounds' (Behrens et al., 2022). This manuscript shows the type of information which can be gleaned from global climate models with dynamic and coupled atmospheric and marine/sea-ice models and is representative of a more in-depth study also including the NZESM which had been under peer-review in the final months of the Challenge.

As well as enabling research and development in coupled climate modelling, the ESM programme within the challenge also facilitated a wide range of other topics in computational climate science. These included:

- Atmospheric model development e.g. Varma et al. (2020) leading to the adoption of code into the core of the 'Unified Model' (UM) weather and climate prediction system, used by weather and climate services in New Zealand, Australia, the UK, the USA, South Korea, South Africa, Poland, India and Singapore.
- Participation in the Aerosol and Chemistry Model Intercomparison Project; running climate models, postprocessing and delivering the data for inclusion in the 6$^{\text{th}}$ Assessment Report of the Intergovernmental Panel on Climate Change e.g. Zeng et al. (2022).
- Provision of a technical support service for UM-based climate model users and developers 'across the motu' – academic and research staff and students – including at NIWA, and at the universities of Otago, Canterbury, and Victoria University of Wellington.

With the cessation of the long-term funding provided by the Challenge to the non-exhaustive list above – and coupled to the recent and ongoing role disestablishments in the science sector – the ability of the New Zealand science system to provide these services going forward is now either severely limited or gone.

Science background

In February 2023, ex-tropical cyclone Gabrielle impacted several countries in the South Pacific and caused the largest financial fallout of any South Pacific tropical cyclone on

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record (Harrington et al., 2023), as well as causing eleven fatalities.

A further example of an ex-tropical cyclone impacting New Zealand came in April 1968 in which cyclone Giselle caused the sinking of the passenger vessel Wahine with the loss of over fifty lives.

Although these two particular storms are far from unique in their physical attributes, they occupy a particularly visceral location in the public psyche of New Zealanders and are used in this study as benchmarks to validate cyclone tracking software.

The scheme of Hodges et al., (Hodges, 1994, 1995, 1999) has been widely used in the literature but is not open-source, although it does track spatial features in atmospheric vorticity bringing the advantage of being able to find storms early in their lifetime.

In this study the stormTracking package is used – www.github.com/ecjoliver/stormTracking – which identifies pressure extrema and their paths through time (Chelton et al., 2011).

The tempestExtremes package(Ullrich et al., 2021) is another open-source project which uses sea-level-pressure data to track storms, and a comparison between the results of these packages is given below. I also provide a comparison of the ability of the 20CR and ERA5 reanalyses to follow the observed track of cyclone Giselle and subsequently use ERA5 because of its higher resolution and its improved ability to capture deep lows.

The study of Roberts et al. (2020) compares the results of TRACK and tempestExtremes using simulations from the High Resolution Model Intercomparison Project, HighResMIP (Haarsma et al., 2016) out to 2050. They find an overall decrease in the number of Southern Hemisphere TCs in the Indian Ocean but results for the Northern Hemisphere and indeed other Southern Hemisphere ocean basins are unclear. They also note, and the present study agrees, that the most damaging TCs are set to get more powerful. Indeed this – along with a general uncertainty concerning TC occurrence frequency – is the broad consensus of the research community at the time of writing.

Some previous studies have found that Southern Hemisphere tropical cyclone frequency is set to reduce as the climate warms yet some have found the opposite, see Chand et al. (2022) for a recent review. In contrast, the strength of TCs is – more robustly – projected to increase (Chand et al., 2022; Emanuel, 2005; Knutson et al., 2010). The number of TCs is also highly dependent on the ocean basin considered with the South Atlantic for example producing few-to-none (Pezza and Simmonds, 2005). Since a climate model with a relatively low resolution is used – see limitations in e.g. Camargo and Wing (2016) – and because of the significant uncertainty in present understanding of future TC frequency noted above, I only consider the average TC severity and do not consider occurrence frequency in this work.

I firstly compare simulated, historical tropical cyclone climatologies in the New Zealand region against reanalysis data and then move on to assessing potential future changes to storms at the end of the 21st century using various different Shared Socioeconomic Pathways. This allows for quantification of the uncertainty inherent in future greenhouse gas emissions (Meinshausen et al., 2020; Riahi et al., 2017).

Comparing tracking algorithms

To better understand the uncertainty associated with the use of different tracking algorithms, I start by comparing the outputs of the stormTracking and tempestExtremes (Peter Gibson, NIWA, Personal communication) packages using ERA5 data from 1989 – 2008 as ground truth, Figure 1.

The minimum storm duration considered is 54 hours – the tempestExtremes default value – and the input data for stormTracking is regridded to a resolution of 2° before the processing algorithm is applied. The reason for this is that the default input dataset to stormTracking is the 20CR reanalysis which has a resolution of 2°. Only storms which have their genesis in -20° $<$ latitude $<$ 0° and 132.7° $<$ longitude $<$ 216.3° are considered. The longitude bounds here are those of the region in recent studies of the effect of the nested high-resolution ocean on coupled model climatologies in Behrens et al. (2020) and Williams et al. (2023).

The agreement between the two results in Figure 1 shows that the two different algorithms are – qualitatively – in good agreement with one another. Perfect agreement is not expected due to different coding methods and parametric (or ‘structural’) assumptions used. For example, stormTracking uses 200 pressure bins, a maximum speed of TC propagation of 80 km/h and a threshold minimum track length of 1000 km, amongst others. Analysis of the sensitivity of the results in this study to changing these parameters was not performed in the time and, ultimately, funding available. For example, this study did not examine the number of systems which were – to within some error – common to both tracking schemes. That said, some are visible by eye, such as the long-lived system which crosses Western Australia – likely cyclone Steve, February-March 2000 – after an extensive, multiple-landfall path across the north of the country.

Overall, the stormTracking results in Figure 1 are more sparse further away from the genesis sites compared to tempestExtremes. As well as the structural differences in the algorithms discussed above, this is likely, in part, due to the regridding which is applied for stormTracking, removing a substantial amount of the spatial information present in the raw data. This is quantified by the number of storms reaching south of -60°, $N_{\lambda<-60}$, which is six in Figure 1(a) and eleven in Figure 1(b).

In summary, for an exploratory study such as this, the overall agreement between the two packages is encouraging and – along with the validation for TCs Giselle and Gabrielle below – gives confidence that the stormTracking software is fit for purpose and is used exclusively for the remainder of this study.

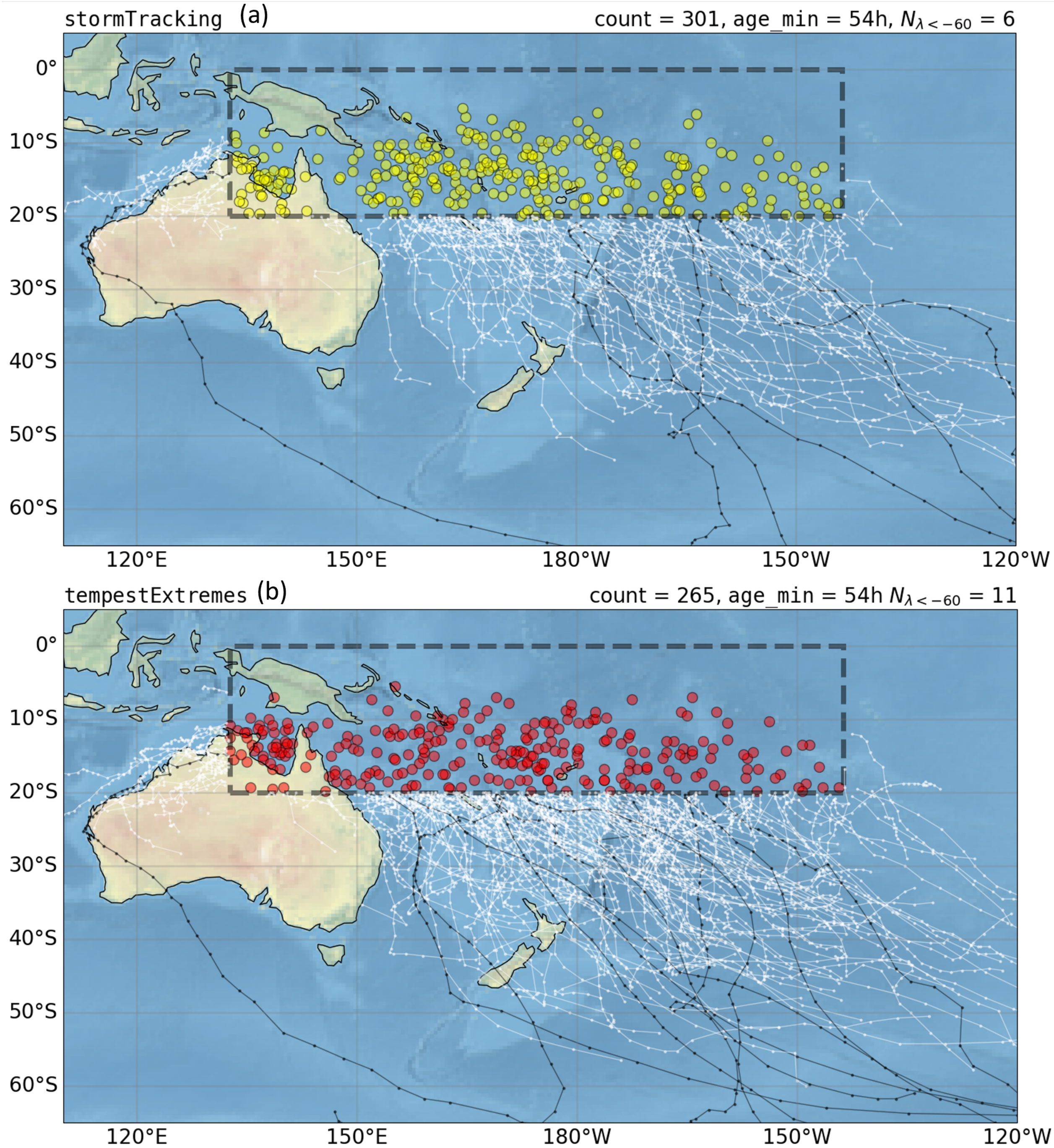

Figure 1: Tropical cyclone climatologies for the stormTracking – (a) – and tempestExtremes – (b) – software packages. The input data is 6-hourly mean-sea-level pressure for 1989-2008 from the ERA5 reanalysis. Only storms with duration 54 hours or more are considered and the black tracks are for storms which reach south of -60°, the sum of which is denoted $N_{\lambda<-60}$. Only storms which have their genesis in -20° < latitude < 0° and 132.7° < longitude < 216.3° are considered.

Validation of storm tracking software

Giselle, April 1968

Cyclone Giselle struck New Zealand and caused the sinking of the passenger ferry Wahine in April 1968. Giselle was an ex-tropical cyclone and its path over the preceding days is shown in Figure 2(a), which shows the track of cyclone Giselle from two perspectives. Firstly from the IBTrACS – The International Best Track Archive for Climate Stewardship – database (Knapp et al., 2010) and secondly by processing raw sea-level pressure data from the 20CR (Compo et al., 2011) and ERA5 (Hersbach et al., 2020) reanalyses. Figure 3(a) shows the central pressures at the same times. Note that in Figures 2 and 3, IBTrACS data is shown from its genesis point in the database until the data specified in the figure caption.

At first sight, it is perhaps not surprising that the three

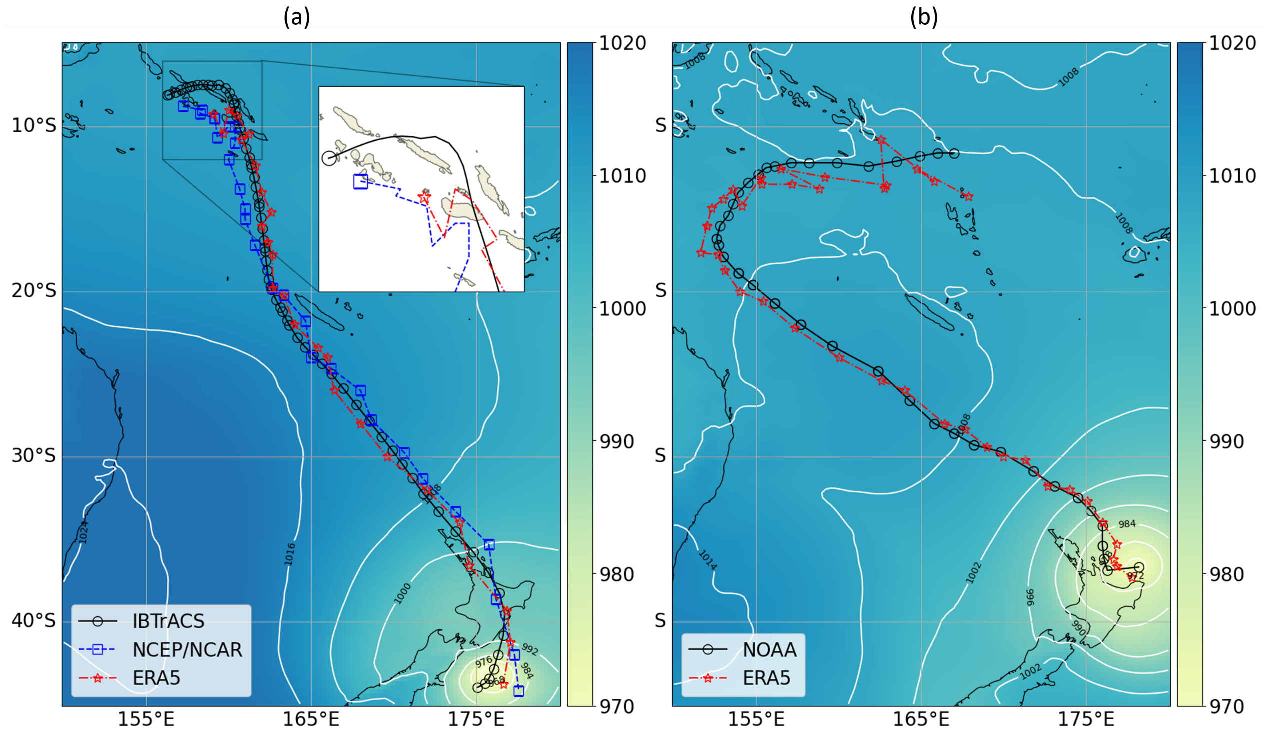

Figure 2: (a) Observed (Knapp et al., 2010) track from IBTrACS of cycle Giselle (circles) which hit Wellington in April 1968 causing the Wahine disaster. All tracks show data from the beginning of the respective datasets and are terminated at 19680410T0600Z – the approximate time of the disaster – which is also the date of the background ERA5 pressure map. The inset zooms in on the cyclogenesis region. (b) Observed track from NOAA of cycle Gabrielle which hit New Zealand in February 2023. Both tracks show data from the beginning of the respective datasets and are terminated at 20230214T0000Z which is also the date of the background ERA5 pressure map. NOAA data for Gabrielle is available at https://www.ssd.noaa.gov/PS/TROP/DATA/ATCF/JTWC/bsh122023.dat.

tracks shown in Figure 2(a) are so similar; they are, after all, representations of the same weather system. However the resolution of the 20CR reanalysis is $2^\circ \times 2^\circ$ and that of ERA5 is 8 times greater, $0.25^\circ \times 0.25^\circ$, i.e. 64 times the areal resolution of 20CR. However, the stormTracking package regrids all data to the same resolution as the 20CR reanalysis, that is, the software's default setting. Note that the extreme low pressure around April 10$^{\text{th}}$ 1968 is well captured by ERA5 but poorly by 20CR in Figure 3(a).

Gabrielle, February 2023

Gabrielle was – by some measures – the most economically damaging event in New Zealand's history (Harrington et al., 2023) and caused the deaths of eleven people. Figure 2(b) and Figure 3(b) show Gabrielle's track and central pressure respectively.

The track data in Figure 2 shows that the stormTracking software does not converge onto the observed track for a couple of days. This is not overtly surprising however since the ERA5 data are regridded before applying the tracking algorithm, as described above. Once the tracks converge, again the agreement between the observed locations and those from the ERA5 data is excellent and the observed central pressures – Figure 3(b) – are closely followed.

Climate model used

I use results from the United Kingdom Earth System Model, version 1, UKESM1 (Sellar et al., 2019, 2020) and compare its results with reanalysis data from ERA5 (Hersbach et al., 2020). UKESM1 is a state-of-the-art, coupled earth system model – ESM – consisting of dynamic atmosphere, land-surface, ocean and sea ice models with the addition of biogeophysical and biogeochemical components (including an explicit troposphere-stratosphere chemistry scheme) and was a constituent model in the CMIP6 ensemble. These additional components of the model are what differentiates an 'Earth System' model from a 'physical' climate model such as the HadGEM3-GC3.1 model (Williams et al., 2018), which is the so-called 'physical core' of UKESM1. Detailed descriptions of all model components can be found in the

SSP 'family'	Scenarios; $\mathcal{F}$ at 2100	Description (overview in O'Neill et al. (2016))
1	1.9, 2.6	*Sustainability* (van Vuuren et al., 2017)
2	4.5	*Middle of the road* (Fricko et al., 2017)
3	7.0	*Regional rivalry* (Fujimori et al., 2017)
5	8.5	*Fossil-fuelled development* (Kriegler et al., 2017)

Table 1: Shared socioeconomic pathways – SSPs – used in this work. The names used throughout this paper are formed by joining the SSP 'family' (1, 2, 3, 5) and the value of $\mathcal{F}$ (1.9, 2.6, 4.5, 7.0, 8.5), e.g. SSP2-4.5. $\mathcal{F}$ is the top of atmosphere radiative forcing at 2100 in $\mathrm{W \cdot m^{-2}}$.

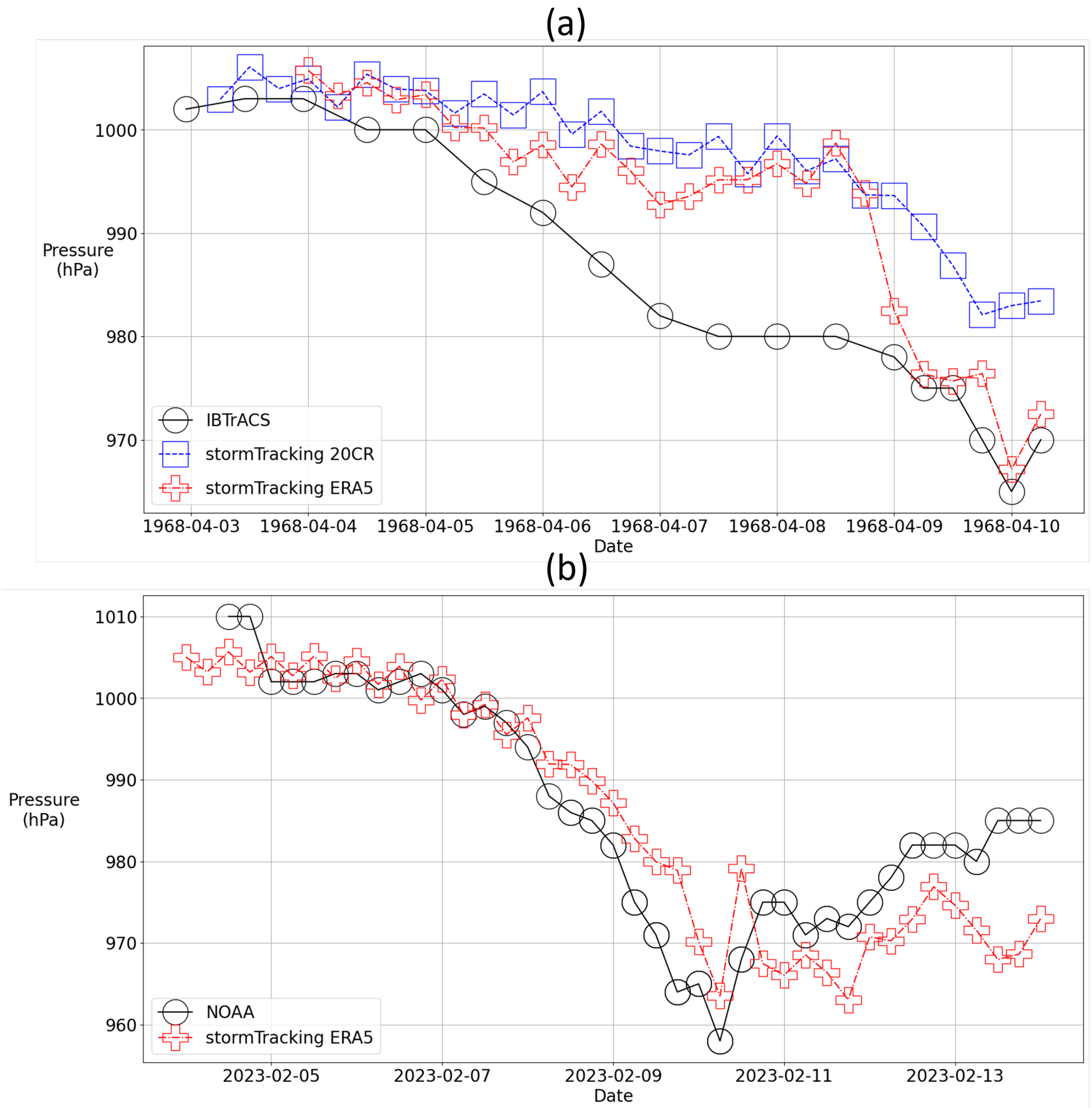

Figure 3: (a) Observed central pressure of storm Giselle from the IBTrACS database (Knapp et al., 2010) and the calculated values from the ERA5 (Hersbach et al., 2020) and 20CR (Compo et al., 2011) reanalyses. (b) Observed central pressure of storm Gabrielle from NOAA – see Figure 2 caption – and the calculated values from the ERA5 (Hersbach et al., 2020) reanalysis.

work of (Sellar et al., 2019). Throughout this work I compare 5-member ensembles of historical results for 1989-2008 and future scenarios for 2080 – 2099. The forcings after 2015 – the end of the 'historical' period for CMIP6 – are described in Table 1.

In this work, the power dissipation index (PDI) is used to quantify the potential change to damage caused by tropical cyclones. The definition of (Emanuel, 2005) is used, in which the damage is proportional to the time-integrated cube of the windspeed at 10 m throughout its trajectory.

Results

Figure 4 shows TCs generated in the New Zealand region; specifically in the longitude band considered in recent studies examining the effect of regional ocean grid refinement on oceanic (Behrens et al., 2020) and atmospheric (Williams et al., 2023) climate. Figure 4 further illustrates why the statistics of storms impacting New Zealand specifically are so sparse. For example in sub-Figures 4(p, r, x) there are no tropical cyclones which impact New Zealand at all, which is consistent with research showing that New Zealand experiences roughly one 'storm of tropical origin' per year (Sinclair, 2002).

Even given the roughly once-a-year occurrence TCs noted above, it is of interest to examine these specific genesis and intersection regions to try and understand what information can be gleaned from wind speeds along the entire track – every six hours – rather than simply counting

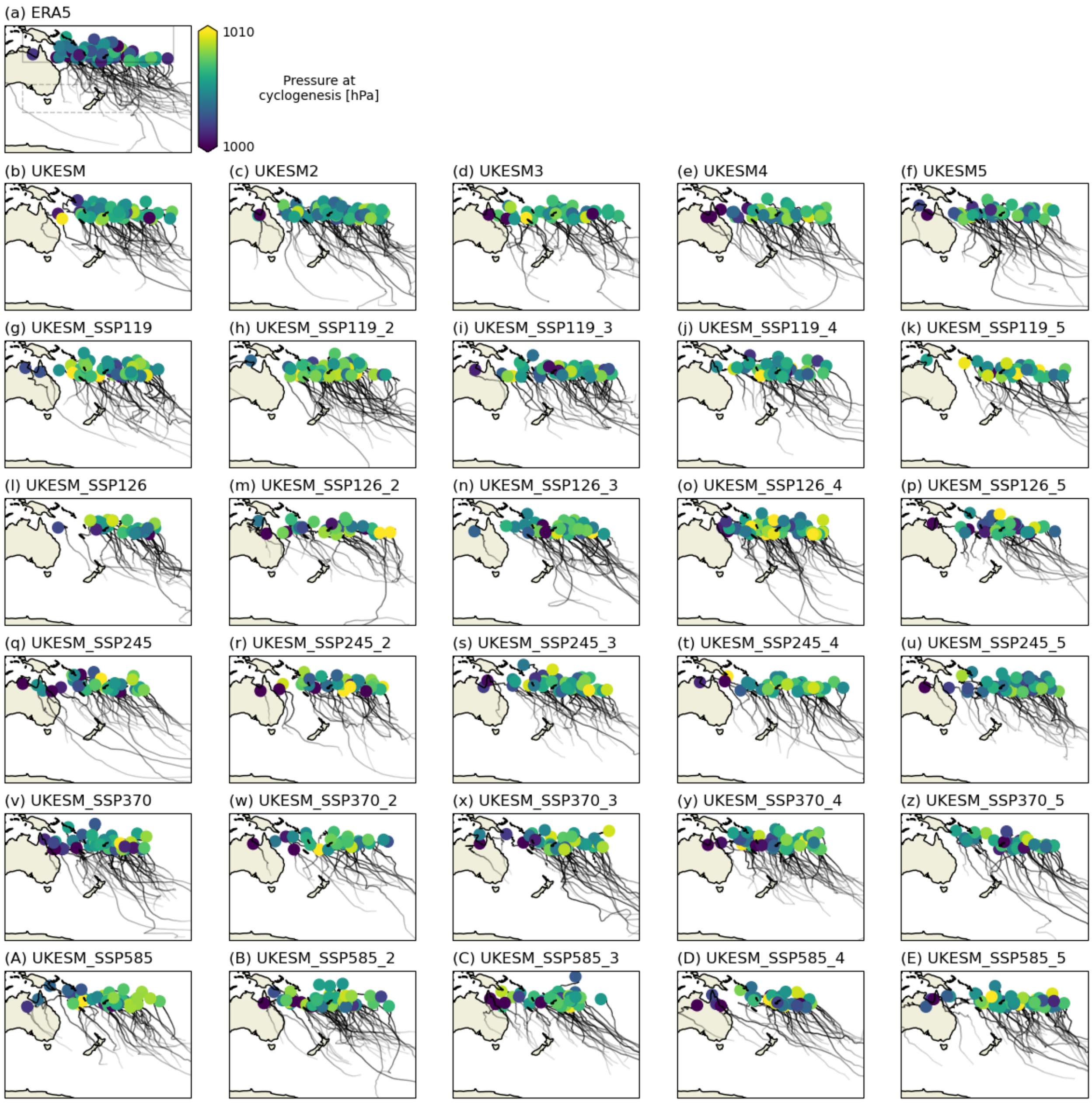

Figure 4: Cyclones formed in the solid box region which intersect the dashed box region – shown in (a) only – for 1989-2008. Both boxes have the same longitude extent as the region described in Behrens et al. (2020). The solid box goes from the equator to -20° S and the dashed box goes from -48.17° to -32.75° S. The pressure at cyclogenesis is shown using a colour bar which is the same for all sub-figures. The transparency of the plotted cyclone tracks decreases from 1 at genesis to 0.1 at termination. (a) ERA5, and UKESM1 simulations, historical (b-f), SSP1-1.9 (g-k), SSP1-2.6 (l-p), SSP2-4.5 (q-u), SSP3-7.0 (v-z) and SSP5-8.5 (A-E).

cyclone occurrence, which clearly only yields one piece of information per system.

Figure 5(a) shows the mean, the individual ensemble members and intra-ensemble spread of the PDI for the 5-member historical and SSP ensembles in Figure 4. In Figure 5(b), the data in Figure 5(a) is recast to take into account the unequal spacing in the $\mathcal{F}$ values for each SSP.

The ensemble spread is large, as reflected by the broad confidence intervals. There is however a clear relationship between PDI and the net radiative forcing at the top of the atmosphere, denoted $\mathcal{F}$ (see Table 1). Indeed, this shows that an increase in PDI per storm of up to 24% with an R^2 value of 0.78 may be expected by 2100 assuming a fossil-fuelled development scenario. The linear fit to the data gives a first order quantification of the increase in potential future storm damage with increased radiative forcing.

The large spread of the results explains why the mean $\mathcal{F}$-PDI relationship only becomes clear at the highest forcings; in the SSP1-1.9 case, one ensemble member in Figure 5(a) has a PDI which is significantly higher than the other four. Preliminary analysis using larger target regions (and hence better statistics) indeed shows a monotonic, positive $\mathcal{F}$-PDI correlation. However, for the purposes of studying Aotearoa New Zealand specifically, I have chosen to display this result alone and encourage the continuation of work in this area.

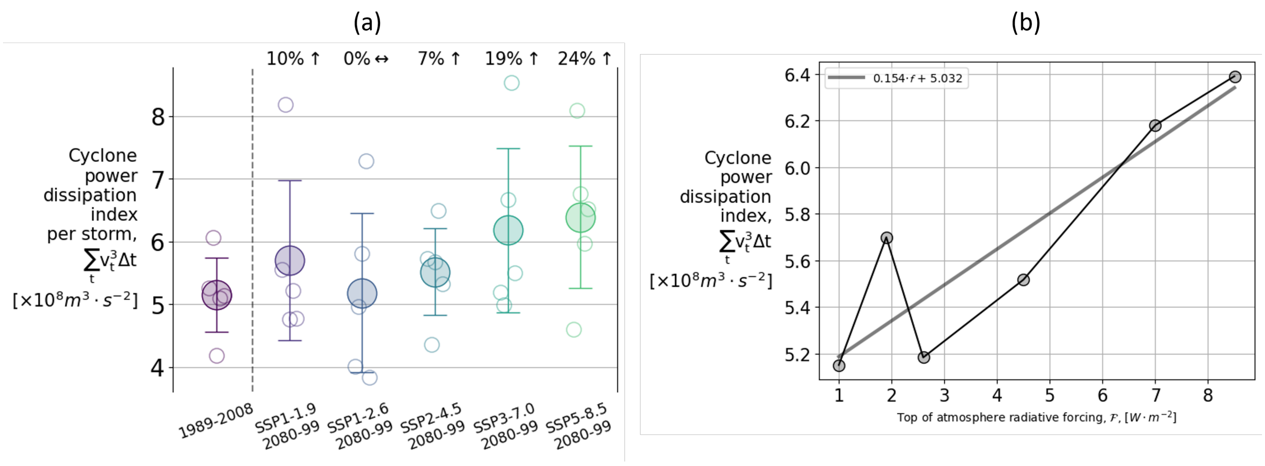

Figure 5: (a) Cyclone power dissipation index – PDI – per storm for the simulated systems shown in Figure 4. (a) Shows the ensemble mean, the 5 individual ensemble members, and ± 1 standard deviation. (b) Mean PDI as a function of the top of atmosphere radiative forcing, $\mathcal{F}$. The best fit line has an R^2 fit value of 0.78.

Conclusions and outlook

In this manuscript the storm climatologies of UKESM1 and reanalysis data relevant to New Zealand have been examined. The stormTracking software used was validated by comparison with another package – tempestExtremes – and by its ability to reproduce the observed track of cyclones Giselle (April 1968) and Gabrielle (February 2023).

For tropical cyclones with their genesis in the New Zealand sector which 'hit' New Zealand latitudes there is a clear increase, albeit with significant uncertainty, in the mean PDI per storm as the top of atmosphere radiative forcing is increased. In this particular example, an increase of up to 24% by 2100 is projected.

Preliminary studies using larger genesis and termination regions give rise to a clearer relationship between radiative forcing and PDI and, although multi-member ensembles were used in the work presented here, the variability is still large. Moreover, the 'impact' region used here – see Figure 4(a) – is much larger than New Zealand itself. Shrinking the termination region further leads to the results being more speculative than prognostic; borne out by the fact that the country only experiences approximately one observed ex-tropical cyclone per year on average.

The increase in the damage potential of future tropical cyclones is a robust – if not always quantified – result with wide agreement in the literature. However, this study does not address downstream changes to multi-hazard impacts such as high winds and tides occurring either simultaneously or from the serial grouping of consecutive events. In this latter case, authorities' and communities' ability to respond to disasters is often made more challenging by the resources already pooled into dealing with the former. Ironically, this is exactly the type of large-scale, persistent and interdisciplinary science that the National Science Challenges were set up to achieve.

2024 has been, to say the least, a challenging year for New Zealand science. The end of the Deep South Challenge – even though the date was known long in advance – was more abrupt than many had hoped. At least partially, the reason for this is that no interim bridging funding materialised, bringing about a "fiscal cliff", as described by the Minister of Science on Radio New Zealand's Nine to Noon programme on March 28th (Concannon and Rykers, 2024).

With this in mind, regarding ongoing climate science in New Zealand, in his April 2024 piece in Newsroom, the Kiwi scientist Dr Kevin Trenberth CNZM – one of the most eminent, highly cited and respected climate scientists in the world – writes (Trenberth, 2024):

'Long-term funding for continuous climate research is needed if New Zealand is to properly understand what weather extremes it may face in the future... there is inadequate work in that area in New Zealand... Too much climate research funding is episodic, not continuous.'

The National Science Challenges provided precisely this kind of persistence, which – to give another example – enabled 'unprecedented' funding of 'urgently needed' kaupapa Māori adaptation projects,[1] i.e. the kind of interdisciplinary projects essential to understand future downstream effects of potentially more powerful TCs on often-isolated communities.

Returning to the specifics of the research showcased above, inevitably, the number of staff working on climate modelling in New Zealand is now rather smaller than it was, something which the Parliamentary Commissioner for the Environment describes as happening 'without any apparent regard for the nation's long term environmental interests' (Upton, 2024).

Indeed, although world-leading climate change researchers remain across the country, our science system is now less able to train the next generation of climate modellers and to contribute to answering the truly global questions which only future generations can ask.

[1]https://www.royalsociety.org.nz/news/deep-south-challenge-to-fund-14-kaupapa-m/

Code and data availability

The stormTracking and tempestExtremes codes are available on GitHub.com at @ecjoliver/stormTracking and @ClimateGlobalChange/tempestextremes respectively. All UKESM1 data is available through the CMIP6 data archive at the Earth System Grid Federation, https://esgf.llnl.gov/. The code describing the implementation of the AGRIF high-resolution ocean is available at Zenodo (Behrens, 2020). The ERA5 reanalysis is available from the European Centre for Medium Range Weather forecasts, https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5. The 20CR reanalysis is provided by the National Oceanic and Atmospheric Administration https://psl.noaa.gov/data/20thC_Rean/.

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