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Fewer deep cyclones projected for the midlatitudes in a warming climate, but with more intense rainfall

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Abstract

Cyclones are a major cause of extreme weather in the extratropics. Projections of future climate change have focussed on extratropical cyclones identified close to the surface, but cyclones identified at multiple levels of the atmosphere ('deep' cyclones) make the largest contributions to total and extreme rainfall. Here we use ten CMIP5 models to assess projected changes in cyclone frequency and associated heavy rainfall between 1979–2005 and 2070–2099 under a high emissions scenario (RCP8.5), with a focus on changes in vertically organised ('deep') systems with cyclones present at both the surface and 500 hPa. We find a robust decrease in the number of deep cyclones by the end of the 21st century, together with an increase in the number of extreme rainfall events caused by deep cyclones. In contrast to deep cyclones, shallow cyclones identified only at the surface are found to produce less rain and are projected to increase in frequency in the future, particularly over land areas. Our findings demonstrate the benefits of considering vertically deep cyclones, as their connection to extreme rainfall has implications for risk assessment and climate adaptation strategies.

1. Introduction

Cyclones are one of the most important weather systems for rainfall, particularly in the middle and high latitudes where they are responsible for more than 70% of both total and extreme precipitation (Hawcroft *et al* 2012, Pfahl and Wernli 2012, Dowdy and Catto 2017). For this reason, several studies have examined future changes in extratropical cyclone frequency and intensity, with projections consistently showing a poleward shift of the southern hemisphere storm track and fewer cyclones in the midlatitudes (Collins *et al* 2013). Projections are less robust in the Northern Hemisphere, although studies indicate potential increases in intense cyclones and cyclone rain (Collins *et al* 2013, Ulbrich *et al* 2013, Zhang and Colle 2017, Raible *et al* 2018). However, these projected changes are based on cyclones identified either at the surface or low levels, with little attention to cyclones higher in the troposphere, despite the sometimes substantial impacts from upper level cyclones including cut-off lows (Dowdy *et al* 2014, Barbero *et al* 2019). Cyclones that are vertically well organised, where a low pressure system can be clearly identified over a range of levels between the surface and 500 hPa, cause heavier rainfall than shallow cyclones identified over a more limited range of levels (Pepler and Dowdy 2020). However, no previous study has examined these vertically organised cyclones, here referred to as 'deep cyclones', in climate models, representing a major knowledge gap in relation to the occurrence of extreme weather in our warming climate.

Regional case studies in Australia have identified stronger projected future declines when cyclones are identified at 500 hPa when compared to projected future changes in surface cyclones (Dowdy *et al* 2014, Pepler *et al* 2016b). This result raises questions as to whether similar patterns can be identified in other regions of the globe, and what that may imply for future changes in cyclone-related total and extreme rainfall. Here we apply a cyclone tracking method to both mean sea level pressure (MSLP) and

500 hPa geopotential height (GPH) data from the ERA5 reanalysis (Hersbach *et al* 2020) and ten global climate models from the fifth Coupled Model Intercomparison Project (CMIP5, Taylor *et al* 2012) set of simulations. This is used to examine the occurrence of deep cyclones that are vertically well organised, and shallow cyclones that are identified only at a single level, including the relative importance of deep and shallow cyclones for total and extreme rainfall. Finally, we assess future changes in the frequency of different types of cyclone and how these contribute to projected changes in total and extreme daily rainfall through different regions of the world.

2. Methods

Cyclones are tracked using the University of Melbourne cyclone tracking scheme (Murray and Simmonds 1991, Simmonds *et al* 1999), available at https://cyclonetracker.earthsci.unimelb.edu.au/, with track data available at Pepler (2021a). In this tracking method, gridded fields are first converted to two hemispheric grids using a polar projection with an approximate resolution of 1.5° at 30° S, with 2° of spatial smoothing applied to remove gridpoint-scale lows. Cyclones are identified as local maxima in the Laplacian of the gridded field, which are then linked with a nearby minimum in the gridded data. Only cyclones which exceed a minimum threshold Laplacian when averaged over a 2° radius from the cyclone centre are retained, with both open and closed depressions included to allow for the lower spatial resolution of CMIP5 models. Cyclones are then joined into tracks using a probability matching technique. Surface cyclones are not tracked where model orography is above 1000 m, noting that the orography varies between models of different resolutions.

Cyclones are tracked using the ERA5 reanalysis (Hersbach *et al* 2020) and ten CMIP5 models (supplementary table S1), which were selected based on previous comprehensive work identifying models with skill at simulating Australian climate including cyclones and major modes of climate variability, while also considering model independence and spanning a broad range of projected future rainfall and temperature changes (CSIRO and Bureau of Meteorology 2015). Only one member was used for each model, with r1i1p1 chosen in all cases except CCSM4, for which r6i1p1 had more data available on Australian computer servers used for this project. Surface cyclones were tracked using 6-hourly MSLP, with an initial minimum intensity threshold of 0.5 hPa (deg. lat.)$^{-2}$. Due to data availability, upper level cyclones were tracked once per day using the daily mean 500 hPa GPH and a minimum intensity threshold of 1 m (deg. lat.)$^{-2}$. ERA5 daily GPH was calculated as the average of the four 6-hourly observations at 0000, 0600, 1200 and 1800 UTC. Cyclones were tracked for all years 1979–2005 in historical simulations and for 2006–2100 using both RCP4.5 and RCP8.5. Change figures mostly show projections for RCP8.5 at the end of the century (2070–2099) to maximise the signal-to-noise ratio in results.

To ensure a fair comparison between simulations, raw cyclone data was post-processed so each model had the same global number of cyclones during the common 1979–2005 period. This was based on the number of surface cyclones in ERA5 during the same period using a threshold of 1 hPa (deg. lat.)$^{-2}$, with the corresponding intensity threshold for other models and 500 hPa cyclones shown in supplementary table S1. Weaker ERA5 thresholds were also tested (0.5 or 0.8 hPa (deg. lat.)$^{-2}$), as well as additional criteria such as a minimum duration of 24 h or a minimum movement of 1000 km (as in Hoskins and Hodges 2005, Neu *et al* 2013), but these choices made little difference to the results.

Cyclones were identified as deep or shallow through a three-step approach. First, an individual cyclone was classified as 'deep' if there was a corresponding low at the other level on the same UTC day within a 500 km radius, to account for the lower temporal resolution of 500 hPa cyclones. Secondly, a cyclone track was classified as 'deep' if it was deep at any time during the track, to allow for the temporal development of cyclones which are most well organised subsequent to the period of heaviest rainfall (Booth *et al* 2018, Pepler and Dowdy 2020). The remaining tracks are classified as 'shallow'. While vertically deep cyclones are typically stronger than shallow cyclones (Pepler and Dowdy 2020), the distinction between 'deep' and 'shallow' cyclones throughout this study is based purely on the vertical organisation of the system rather than incorporating intensity information. This is in contrast to some previous studies which have used the term 'deep' to describe a strong or intense subset of cyclones which may or may not have upper level development. This method does not require a unique match, so an individual upper low could potentially be associated with multiple surface lows during its track. This allows the classification of both surface and upper lows independently into 'deep' and 'shallow' subsets.

The locations of all cyclones on a given day were expanded such that they influence the surrounding 10°, consistent with the observed radius of cyclone-associated rainfall (Hawcroft *et al* 2012, Utsumi *et al* 2017, Booth *et al* 2018). The region of cyclone influence was calculated on the model grid, so will differ slightly between models based on their resolution. A point was classified as influenced by a deep cyclone on a given day if it was influenced by either a deep surface or a deep upper cyclone; a shallow surface cyclone if it was influenced by a shallow surface cyclone but no deep cyclone; and a shallow upper cyclone if there was a shallow upper cyclone but no deep or shallow

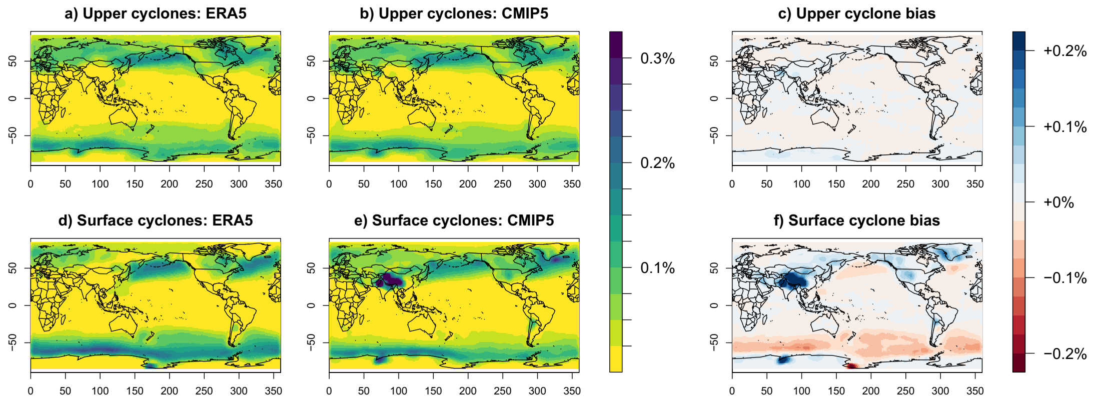

Figure 1. Mean frequency of upper (top) and surface (bottom) cyclones in ERA5 (left) and the CMIP5 ensemble mean (centre) during 1979–2005, expressed as percentage of observations with a cyclone centre identified for each 1° × 1° grid cell. (right) CMIP5 mean bias, expressed as the mean absolute difference in cyclone frequency using the same units. Mean frequency is averaged over a 5° smoothing radius for ease of interpretation.

surface system. Testing showed that there was little overlap between these three categories.

Cyclones from each model were associated with daily rainfall on the model grid, with the exception of ERA5, which was first bilinearly regridded to 1° to increase analysis speed, with cyclone rainfall data available at Pepler (2021b). This was achieved by converting the three cyclone categories into a binary mask used to multiply the daily rainfall prior to calculating a monthly sum for each category. In addition to total cyclone-related rainfall, we calculate the number of days with extreme rainfall. This is defined as the number of days greater than or equal to the local 99.7th percentile calculated from all days during the 1979–2005 period, which would be exceeded once per year on average in the current climate. Rain days were defined as days when rainfall was at least 1 mm, to exclude days with very low rainfall which are overestimated in climate models (Stephens *et al* 2010), and the rain rate for a given cyclone category was calculated by dividing the total rainfall by the number of days. Mean values over the present (1979–2005) and future (2070–2099) periods were calculated for each model on the model grid prior to bilinearly regridding to a common 1° grid to allow the production of ensemble-mean figures.

Latitude mean changes in cyclone rainfall or frequency were calculated by taking the sum of all cyclones (or all cyclone rainfall) in a given latitude or latitude band in the future climate, and dividing by the sum across the whole latitude band in the current climate. Statistical significance of latitudinal mean changes is assessed for each model using a two-tailed t-test on annual (or seasonal) data, with results considered significant for $p < 0.05$. The latitude bands used for analysis were based on the relative dominance of deep cyclones in figure 1, and defined as the polar regions (poleward of 75°); the extratropics (45–75°) where deep cyclones produce at least 50% of rainfall; the subtropics (15–45°) where deep cyclones are less common but remain an important cause of heavy rainfall; and the tropics (15° S to 15° N). Although results are presented globally for completeness, the focus of this study's analysis and conclusions are on extratropical regions including the midlatitudes and subtropics, for which the cyclone identification scheme is optimised; such methods are less effective at identifying tropical cyclones (equatorward of 20°), particularly at climate model resolutions (e.g. Dowdy and Catto 2017).

3. Results

Using model-dependent thresholds that give the same total number of cyclones across the globe, the CMIP5 models produce broadly similar spatial patterns of cyclone frequency to those based on ERA5 reanalysis data (figure 1), with highest frequencies in the extratropics. However, when cyclones are identified using MSLP, the CMIP5 models consistently generate too many cyclones over northern hemisphere land areas, particularly near elevated topography such as the Himalayas. This is likely a consequence of the poor representation of topography in coarse-resolution models, and issues in the extrapolation of model pressure to sea level. In comparison, cyclones are less frequent than in ERA5 over the global oceans, particularly in the southern hemisphere midlatitudes.

In comparison to surface cyclones, upper cyclones are less influenced by topography and show less longitudinal variation in frequency. The CMIP5 models are well able to simulate these features, with consistently lower biases than the models produce for surface cyclones. This suggests that an increased focus on upper cyclones may help to improve the reliability of future cyclone projections (e.g. Dowdy *et al* 2014). The CMIP5 models consequently have fewer deep cyclones in the southern hemisphere when

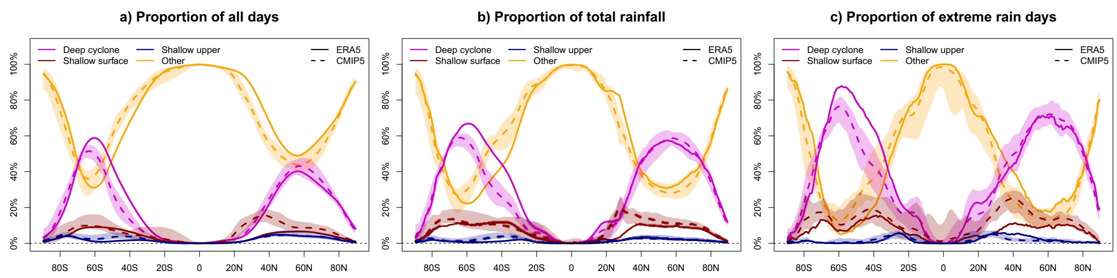

Figure 2. (a) The percentage of days per year with a deep, shallow surface, or upper cyclone identified within a 10° radius of a given location, averaged across each latitude band for 1979–2005. Solid lines show results based on ERA5 reanalysis data, shading shows the range across ten CMIP5 models with their ensemble mean shown as a dashed line. (b) Percentage of total rainfall that occurs on days with a cyclone centre within a 10° radius (or other days). (c) Percentage of days with rainfall above the local 99.7th percentile that have a cyclone centre within a 10° radius (or other days).

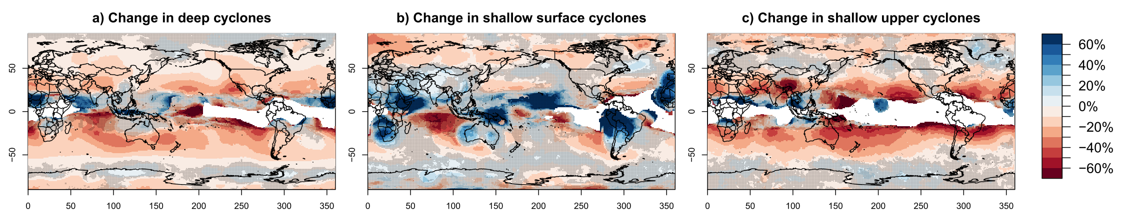

Figure 3. Ensemble mean change in the occurrence frequency of (a) deep, (b) shallow surface and (c) shallow upper cyclones between 1979–2005 and 2070–2099 under a high emissions scenario. Grey stippling indicates where fewer than three quarters (8/10) of the models agree on the sign of the change. Changes are only shown where there is at least one cyclone per year in the historical period.

compared to ERA5, and a higher frequency of shallow surface cyclones in the northern hemisphere (figure 2, supplementary figure S1 (available online at stacks.iop.org/ERL/16/054044/mmedia)).

Deep cyclones are most common between 45° and 75°, which we will refer to as the extratropics, where 42% of locations globally are influenced by a deep cyclone at least once on a given day based on ERA5 data (figure 2(a)). Both deep and shallow cyclones are more common in each hemisphere during the cooler months of the year (not shown). Consistent with their high annual frequency, deep cyclones explain 55% of annual rainfall and 70% of extreme rain days above the local 99.7th percentile in the global extratropics in ERA5 (figures 1(b) and (c)). Deep cyclones also play a very important role in precipitation in the midlatitude and subtropical regions between 15° and 45°, which we will refer to as the subtropics. In these regions they explain 11% of days but 23% of rainfall and 36% of extreme rain days using ERA5 data, which is broadly symmetrical between the two hemispheres.

Shallow surface cyclones also explain a larger proportion of extreme rain days in the subtropics than would be expected from their average frequency, whereas shallow upper cyclones with no surface low are less likely to produce notable rainfall. The results based on CMIP5 models are broadly similar to those based on ERA5 reanalysis data, although the models underestimate the contribution of deep cyclones to total and extreme rain in much of the southern hemisphere, while overestimating the frequency of shallow cyclones and their contribution to extreme rainfall in the northern hemisphere midlatitudes, consistent with biases in surface cyclone frequency at these latitudes.

The frequency of deep cyclones is projected to decrease across most of the globe (figure 3(a)). Projected changes are strongest in the southern hemisphere subtropics (15–45° S) where all ten models have a statistically significant decrease in deep cyclone frequency under RCP8.5, with a multimodel mean decline of 20% (range: −28% to −14%). Projected declines in deep cyclone frequency in this region are also statistically significant for all models under a more moderate emission scenario (RCP4.5), with a mean projected decline of −10%.

All ten models also project a statistically significant decline in the frequency of deep cyclones in the northern hemisphere subtropics, with a mean decline of −15% under RCP8.5 (range: −20% to −11%). Projected declines in deep cyclone days are smaller but remain statistically significant for all models in the northern hemisphere extratropics (mean: −7%) and southern hemisphere extratropics (mean: −4%), noting that the historical average annual frequencies are higher in these regions. At least eight of the nine models with available data also have statistically significant declines projected for these regions using the RCP4.5 emissions scenario, averaging −9% for the

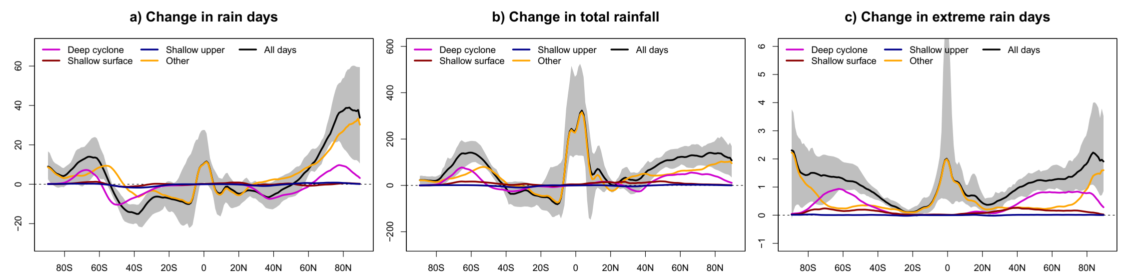

Figure 4. Latitudinal mean difference between 1979–2005 and 2070–2099 under RCP8.5 in (left) frequency of rain days per year, (centre) total annual rainfall (mm) and (right) number of extreme rain days per year. Black line shows the total change, with the grey shading indicating the ensemble range. Coloured lines indicate the mean change related to each cyclone type and all other days.

northern hemisphere subtropics, −4% for the northern hemisphere extratropics and −3% for the southern hemisphere extratropics.

In contrast, the frequency of shallow surface cyclones is expected to increase over many land areas (figure 3(b)), particularly during the warmer half of the year (supplementary figure S3). All models except CNRM-CM5 project an increase in the number of shallow surface cyclones in the southern hemisphere subtropics during November–April under RCP8.5, with a mean increase of +10%, although this is only statistically significant for six models. Similarly, eight of the ten models project an increase in shallow surface cyclones in the northern hemisphere subtropics during May–October (mean: +10%), which is statistically significant in seven cases. This projected increase may include more heat lows as land masses warm, although it is likely to include a range of other rain-bearing lows such as small lows embedded in surface troughs (Pepler and Dowdy 2020), which may become increasingly common with warmer sea surface temperatures (Pepler *et al* 2016b). When assessing all surface cyclones, these opposing changes are conflated, leading to weaker and less robust projected declines in all surface cyclones over land areas, compared to the stronger declines projected for cyclones identified at 500 hPa (supplementary figure S4).

There is a robust decrease projected in the frequency of rain days in the southern hemisphere subtropics (figure 4(a)), with on average 8% fewer rain days in 2070–2099 compared to 1970–2005 under RCP8.5, which is statistically significant for all models. A large part of that decline can be explained by the projected 21% decrease in the number of rain days due to deep cyclones in this region (ensemble range: −15% to −26%). The northern hemisphere subtropics are expected to see 14% fewer deep cyclone rain days by 2070–2099 (ensemble range: −9% to −19%). Nine of the ten models also project a statistically significant decline in the total rainfall from deep cyclones in the southern hemisphere subtropics under RCP8.5 (mean change: −9%), and projected declines are also statistically significant for five models under RCP4.5 (mean change: −5%).

All models project a statistically increase in the global number of heavy rain days under both emissions scenarios, with a mean increase of +95% under RCP8.5 (ensemble range: +57% to +123%) and +44% under RCP4.5 (range: +24% to +55%). The frequency of extreme rainfall increases for all categories, and is dominated by increases in heavy rainfall from non-cyclone days at the tropics and poles, and in heavy rainfall from deep cyclones in the extratropics. The frequency of extreme rain days is expected to increase in most latitudes, even where mean rainfall is projected to decline (figure 4(c)). In the subtropics from 15–45° there is a projected 46% increase in the frequency of extreme rainfall associated with deep cyclones under RCP8.5, despite the projected decline in cyclone frequency, which is statistically significant for all models. This amounts to an average of one extra deep cyclone day with extreme rainfall per decade for each gridpoint in the southern hemisphere subtropics and two extra deep cyclone days with extreme rain per decade in the northern hemisphere subtropics.

In both the midlatitudes and the extratropics, there is a larger projected increase in extreme rainfall from deep cyclones than would be expected from changes in cyclone frequency alone. This is due to a projected increase in the average intensity of cyclone rainfall. Averaged across all areas of the globe with at least one cyclone per year, the average daily rain rate on deep cyclone days is projected to increase by 27% under a high emissions scenario (+15% under a moderate emissions scenario). Similar increases in rainfall intensity are projected for shallow surface and shallow upper cyclones, with a smaller increase in rainfall intensity for days with no cyclone detected (ensemble mean: +15%). This means that the proportion of deep cyclones which are associated with extreme rain is projected to increase globally from 0.6% in the historical simulations to 0.9% in 2070–2099 under a moderate emissions scenario, and 1.2% under a high emissions scenario.

These results are consistent with an increase in atmospheric moisture availability on a warming planet associated with the Clausius–Clapeyron

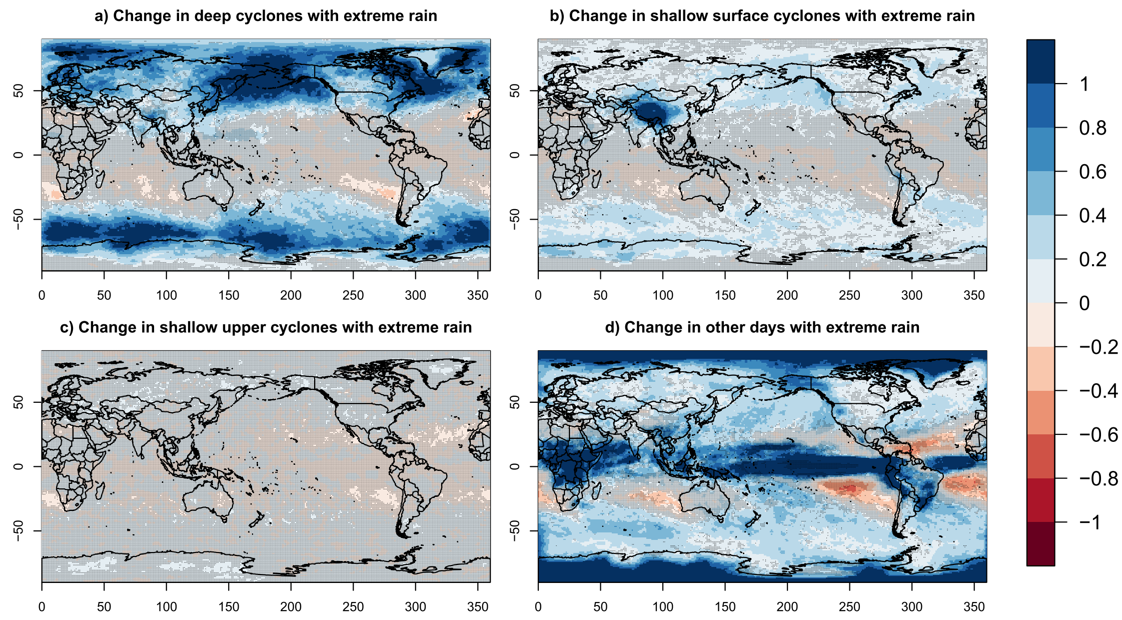

Figure 5. Absolute change in the number of days per year with extreme rainfall, based on an ensemble of ten climate models, showing the difference from the period 1979–2005 to the period 2070–2099 under a high emissions scenario (RCP8.5). Results are presented for days that have (a) a deep cyclone, (b) a shallow surface cyclone, (c) a shallow upper cyclone, or (d) no identified cyclone in a given region. Grey stippling indicates where fewer than eight of the ten models agree on the sign of the change.

relationship of 7% K^{-1}, which can contribute to increased intensity of heavy rainfall events (Schneider *et al* 2010). These results are also consistent with previous studies which have projected an increase in the intensity of cyclone-related rainfall in several regions of the globe (Pepler *et al* 2016b, Yettella and Kay 2017, Zhang and Colle 2017, Raible *et al* 2018, Cavicchia *et al* 2020, Reboita *et al* 2020). Projected increases in rainfall intensity are largest in the tropics and close to the poles (supplementary figure S5), but more mixed in the midlatitudes, where the average rain rate is likely to decline in some areas on days with no cyclone identified, consistent with projected declines in rain days.

The increase in extreme rain days associated with deep cyclones is projected to occur broadly across the northern hemisphere, as well as across large parts of the southern hemisphere (figure 5). Projected increases are largest in parts of the North Pacific and northwest Atlantic, noting that the relatively short historical period used in this study (1979–2005) may not capture long-term climatological variability in cyclone occurrence in these regions (Varino *et al* 2019). Little change or a small increase in cyclone-related extreme rain days is projected for many southern hemisphere land areas even in locations where the total number of deep cyclones is expected to decline, highlighting a strong increase in the intensity of rainfall per deep cyclone in those cases. This is particularly notable in areas where SSTs are projected to warm most strongly, such as off the east coast of Australia, where rain rates are expected to increase for all cyclone categories (supplementary figure S5). In contrast to the number of extreme rain days, projected declines in deep cyclone numbers in these regions are likely to result in fewer rain days and lower total rainfall. These results clearly demonstrate the value in considering cyclones over a range of levels, particularly the occurrence of deep cyclones, when considering future projected changes, as their large contribution to mean rainfall and extremes may result in major impacts on water availability and flood risk (Seneviratne *et al* 2012).

There is also a projected increase in the frequency of extreme rainfall from shallow surface cyclones in the midlatitudes and extratropics. In addition to an increase in the overall frequency of shallow surface cyclones over land areas (figure 3(b)), the likelihood that a shallow surface cyclone will produce extreme rain is also expected to increase across the globe, from 0.55% to 1.1% of cyclones. This increase in extreme rainfall from shallow surface cyclones is particularly notable around the east coasts of continents (including near the Gulf Stream, the Tasman Sea, and east of South America) where rapidly warming sea surface temperatures may contribute to additional moisture and latent heat release for convective systems that can contribute to the occurrence of extreme rainfall (Pepler *et al* 2016a).

Although cyclone climatologies have been previously found to be sensitive to the choice of tracking method used, particularly due to differences in the number of weak cyclones (Neu *et al* 2013, Ulbrich *et al* 2013, Rudeva *et al* 2014, Grieger *et al* 2018) our results are robust to a range of parameter choices including cyclone intensity thresholds and minimum distance criteria. However, as the southern hemisphere midlatitudes are a key region where deep cyclones and their associated rainfall is projected to decline, the underestimation of deep cyclones by CMIP5 models could potentially mean that projected future declines in total rainfall are also underestimated in these regions.

4. Conclusions

By the end of the 21st century, climate models project a robust decline in the frequency of vertically well-organised 'deep' cyclones, particularly in the southern hemisphere midlatitudes, although an increase in average cyclone rain rates means there may simultaneously be an increase in cyclone-related heavy rain. The average rainfall intensity on deep cyclone days increases by 27% in this study, which is broadly similar to what could be expected from thermodynamics alone based on 3 °C–4 °C of global warming and the Clausius–Clapeyron relationship of 7% K^{-1} (Schneider *et al* 2010, Raible *et al* 2018). At the same time, there is a projected increase in the frequency of shallow cyclones identified only at the surface, particularly over land areas and during the warm half of the year, which could reflect an increased incidence of heat lows as the land surface warms.

While previous studies have projected future declines in cyclone frequency in the southern hemisphere midlatitudes (Grieger *et al* 2014, Pepler *et al* 2016b, Reboita *et al* 2020) and increases in cyclone-related extreme rainfall (Yettella and Kay 2017, Zhang and Colle 2017, Raible *et al* 2018), such studies have focused purely on surface cyclones. The results in this paper highlight the importance of considering upper cyclones in projections (Dowdy *et al* 2014), due to both their stronger projected changes and their better representation by coarse-resolution global models. We also highlight the value in using a multi-level approach when tracking cyclones, rather than only considering a single level, as vertically well organised (deep) cyclones are critically important for total rainfall and heavy rain events in the subtropics and extratropics (Lim and Simmonds 2007, Lakkis *et al* 2019, Pepler and Dowdy 2020). The projected increase in shallow surface cyclones over land areas means that studies which have projected cyclones based on MSLP alone may underestimate potential future declines in those cyclones which bring the majority of rainfall, and miss important changes in the structure and characteristics of cyclones influencing land areas.

Data availability

The raw gridded data used for this study (6-hourly sea level pressure, daily 500hPa GPH, and daily total precipitation) were accessed from the Australian National Computational Infrastructure (NCI), and are publicly available from the data providers. ERA5 data is directly available from the European Centre for Mid-Range Weather Forecasting via the Copernicus Climate Change Service at https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview, while CMIP5 data is available from the respective modelling centres and the Earth System Grid Federation at https://esgf-node.llnl.gov/projects/cmip5/.

The cyclone tracks generated as part of the study, as well as the key input files for the cyclone tracking, are available at https://doi.org/10.6084/m9.figshare.13393172. Post-processed grids of cyclone-associated rainfall for the 1979–2005 and 2070–2099 are available at https://doi.org/10.6084/m9.figshare.13393840.

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Code availability

The cyclone tracking used in this paper is available freely online at https://cyclonetracker.earthsci.unimelb.edu.au/, and the associated input files are available with the output track files at 10.6084/m9.figshare.13393172. Example wrapper scripts for converting netCDF files to suitable input formats and post-processing output files are available at https://github.com/apepler/cyclonetracking

Data analysis and figure generation was performed using the R and NCL programming languages. Code used to generate intermediate files, figures, and data for this paper are available at https://github.com/apepler/DeepCycloneTracking

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References

Barbero R, Abatzoglou J T and Fowler H J 2019 Contribution of large-scale midlatitude disturbances to hourly precipitation extremes in the United States *Clim. Dyn.* **52** 197–208

Booth J F, Naud C M and Jeyaratnam J 2018 Extratropical cyclone precipitation life cycles: a satellite-based analysis *Geophys. Res. Lett.* **45** 8647–54

Cavicchia L, Pepler A, Dowdy A, Evans J, Di Luca A and Walsh K 2020 Future changes in the occurrence of hybrid cyclones: the added value of cyclone classification for the east Australian low-pressure systems *Geophys. Res. Lett.* **47** e2019GL085751

Collins M *et al* 2013 Chapter 12—Long-term climate change: projections, commitments and irreversibility *Climate Change 2013: The Physical Science Basis. IPCC Working Group I Contribution to AR5* ed IPCC (Cambridge: Cambridge University Press)

CSIRO and Bureau of Meteorology 2015 *Climate Change in Australia Projections for Australia's Natural Resource Management Regions: Technical Report*

Dowdy A J and Catto J L 2017 Extreme weather caused by concurrent cyclone, front and thunderstorm occurrences *Sci. Rep.* **7** srep40359

Dowdy A J, Mills G A, Timbal B and Wang Y 2014 Fewer large waves projected for eastern Australia due to decreasing storminess *Nat. Clim. Chang.* **4** 283–6

Grieger J, Leckebusch G C, Donat M G, Schuster M and Ulbrich U 2014 Southern Hemisphere winter cyclone activity under recent and future climate conditions in multi-model AOGCM simulations *Int. J. Climatol.* **34** 3400–16

Grieger J, Leckebusch G C, Raible C C, Rudeva I and Simmonds I 2018 Subantarctic cyclones identified by 14 tracking methods, and their role for moisture transports into the continent *Tellus* A **70** 1–18

Hawcroft M K, Shaffrey L C, Hodges K I and Dacre H F 2012 How much Northern Hemisphere precipitation is associated with extratropical cyclones? *Geophys. Res. Lett.* **39** L24809

Hersbach H *et al* 2020 The ERA5 Global Reanalysis *Q. J. R. Meteorolog. Soc.* **146** 1999–2049

Hoskins B J and Hodges K I 2005 A new perspective on Southern Hemisphere storm tracks *J. Clim.* **18** 4108–29

Lakkis S G, Canziani P, Yuchechen A, Rocamora L, Caferri A, Hodges K and O'Neill A 2019 A 4D feature-tracking algorithm: a multidimensional view of cyclone systems *Q. J. R. Meteorolog. Soc.* **145** 395–417

Lim E-P and Simmonds I 2007 Southern hemisphere winter extratropical cyclone characteristics and vertical organization observed with the ERA–40 data in 1979-2001 *J. Clim.* **20** 2675–90

Murray R J and Simmonds I 1991 A numerical scheme for tracking cyclone centres from digital data. Part I: development and operation of the scheme *Aust. Meteorol. Mag.* **39** 155–66

Neu U *et al* 2013 Imilast: a community effort to intercompare extratropical cyclone detection and tracking algorithms *Bull. Am. Meteorol. Soc.* **94** 529–47

Pepler A S, Alexander L V, Evans J P and Sherwood S C 2016a The influence of local sea surface temperatures on Australian east coast cyclones *J. Geophys. Res.* **121** 13352–63

Pepler A S *et al* 2016b Projected changes in east Australian midlatitude cyclones during the 21st century *Geophys. Res. Lett.* **43** 334–40

Pepler A 2021a CMIP5 global cyclone tracks. figshare. Dataset. (https://doi.org/10.6084/m9.figshare.13393172)

Pepler A 2021b CMIP5 global cyclone rainfall. figshare. Dataset. (https://doi.org/10.6084/m9.figshare.13393840)

Pepler A and Dowdy A 2020 A three-dimensional perspective on extratropical cyclone impacts *J. Clim.* **33** 5635–49

Pfahl S and Wernli H 2012 Quantifying the relevance of cyclones for precipitation extremes *J. Clim.* **25** 6770–80

Raible C C, Messmer M, Lehner F, Stocker T F and Blender R 2018 Extratropical cyclone statistics during the last millennium and the 21st century *Clim. Past* **14** 1499–514

Reboita M S *et al* 2020 Future changes in the wintertime cyclonic activity over the CORDEX-CORE southern hemisphere domains in a multi-model approach *Clim. Dyn.* (https://doi.org/10.1007/s00382-020-05317-z)

Rudeva I, Gulev S K, Simmonds I and Tilinina N 2014 The sensitivity of characteristics of cyclone activity to identification procedures in tracking algorithms *Tellus* A **66** 1–20

Schneider T, O'Gorman P A and Levine X J 2010 Water vapor and the dynamics of climate changes *Rev. Geophys.* **48** 1–22

Seneviratne S I *et al* 2012 Changes in climate extremes and their impacts on the matural physical environment *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC)* ed C B Field *et al* (Cambridge: Cambridge University Press) pp 9781107025

Simmonds I, Murray R J and Leighton R M 1999 A refinement of cyclone tracking methods with data from FROST *Australian Meteorological Magazine* **Special Issue** 35–49

Stephens G L *et al* 2010 Dreary state of precipitation in global models *J. Geophys. Res.: Atmos.* **115** D24211

Taylor K E, Stouffer R J and Meehl G A 2012 An overview of CMIP5 and the experiment design *Bull. Am. Meteorol. Soc.* **93** 485–98

Ulbrich U *et al* 2013 Are greenhouse gas signals of Northern Hemisphere winter extra-tropical cyclone activity dependent on the identification and tracking algorithm? *Meteorol. Z.* **22** 61–8

Utsumi N, Kim H, Kanae S and Oki T 2017 Relative contributions of weather systems to mean and extreme global precipitation *J. Geophys. Res.: Atmos.* **122** 152–67

Varino F, Arbogast P, Joly B, Riviere G, Fandeur M L, Bovy H and Granier J B 2019 Northern Hemisphere extratropical winter cyclones variability over the 20th century derived from ERA-20C reanalysis *Clim. Dyn.* **52** 1027–48

Yettella V and Kay J E 2017 How will precipitation change in extratropical cyclones as the planet warms? Insights from a large initial condition climate model ensemble *Clim. Dyn.* **49** 1765–81

Zhang Z and Colle B A 2017 Changes in extratropical cyclone precipitation and associated processes during the twenty-first century over eastern North America and the western atlantic using a cyclone-relative approach *J. Clim.* **30** 8633–56