# Future changes in the occurrence of hybrid cyclones: the added value of cyclone classification for the east Australian low pressure systems.

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**Key Points:**

- A physically-based classification of hybrid cyclones is applied to an ensemble of regional climate model simulations.
- The cyclone classification method adds value to the projections of future cyclone activity, making them more robust.
- Results indicate future changes (2060-2079) towards more intense impacts associated with hybrid cyclones.

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## Abstract

Several regions of the world, including the east coast of Australia, are characterized by the occurrence of low pressure systems with a range of different dynamical structures, including tropical, extra-tropical and hybrid cyclones. Future changes in the occurrence of cyclones are better understood if storms are classified according to their dynamical structure. Therefore, we apply a classification of cyclones according to their cold core or warm core structure to an ensemble of regional climate model simulations.

First, we show that historical simulations reproduce well the reanalysis results in terms of cyclone classification. We then show that once cyclone classification is applied, projections of future cyclone activity become more robust, including a decrease in the occurrence of both cold-core and warm-core cyclones. Finally we show that in a warmer climate warm core hybrid cyclone activity could increase close to the coast, while the associated rainfall and wind are projected to increase.

## Plain Language Summary

Cyclones in the tropics derive their energy from the temperature difference between warm ocean waters and the atmosphere and their interior is warmer than the environment (warm core), while cyclones in the mid-latitudes derive their energy from differences in the atmospheric temperature and density at different locations and their interior is colder than the environment (cold core). In subtropical regions both types of cyclone can form. Also in those regions cyclones known as hybrid cyclones form, with mixed tropical-extratropical features, such as a partial lower-tropospheric warm core and a partial upper-tropospheric cold core. This study is focused on cyclones along the eastern coast of Australia.

Here we show that dividing cyclones in different classes according to their thermal structure provides a better framework to interpret changes in cyclone activity at subtropical latitudes. This study has two main results. First: classifying cyclones adds value to climate projection robustness. A large number of models agree on the decrease in the occurrence of both cold-core and warm-core cyclones. The study also indicates increased occurrence of hybrid cyclones close to the Australian coast. Second: the study shows evidence of future changes in cyclone-related impacts, such as an increase in the associated rainfall.

## 1 Introduction

Low pressure systems frequently occur along the eastern coast of the Australian continent (Dowdy et al., 2019). Extreme weather associated with these lows, such as strong winds, heavy rains and storm surges, can cause severe damage and deaths (Power & Callaghan, 2016) in the densely populated coastal areas affected by the cyclones (Mills et al., 2010; Callaghan & Power, 2014). On the other hand, a large part of the water availability in the region's reservoirs is linked to these cyclones (Pepler & Rakich, 2010). Therefore, accurate projections of possible future changes in east coast cyclone activity are crucial for the purpose of disaster risk reduction and water resource planning.

Several previous studies have addressed possible future changes in cyclone activity along the east Australian coast. Studies based on global circulation models (GCMs) examined mid-to upper-tropospheric signatures of cyclone activity (Dowdy, Mills, & Timbal, 2013), indicating a future decrease in the number of events particularly during the cooler months of the year.

Other studies used an ensemble of regional climate models that have a finer spatial resolution based on dynamical downscaling from GCMs and thus allow for a better representation of some fine-scale cyclone properties (Pepler et al., 2015; Ji et al., 2015).

A more recent study (Pepler, Di Luca, et al., 2016) based on an ensemble of regional climate models (RCM) and comparing different detection methods found a seasonality in the cyclone activity climate change signal, with the cold season characterized by a robust decrease, while the warm season shows a much larger uncertainty in the response to climate drivers. It was found moreover that there is a low agreement among the ensemble members on the changes of cyclone activity at different location within the region, hindering the assessment of possible changes of cyclone impacts.

In recent years, several studies focused on hybrid cyclone occurrence (as reviewed in da Rocha et al. (2018) and references therein). Hybrid cyclones have a vertical structure showing features partially similar to both tropical cyclones and extra-tropical cyclones. In particular, they have a warm core in the lower part of the troposphere and a cold core in the upper part. While low pressure systems are traditionally classified as either tropical or extra-tropical systems and studied separately, it has been shown by a number of recent studies that there are several regions across the world at latitudes between the tropics and the extra-tropics where a large fraction of cyclones have hybrid features (Yanase et al., 2014).

The Australian east coast is one of the regions characterized by the occurrence of cyclones with hybrid features (Garde et al., 2010; Pezza et al., 2014; Cavicchia et al., 2018). It has been estimated that between a third and one half of all cyclones forming in the region have prevailing or partial hybrid features (Cavicchia et al., 2019; Quinting et al., 2019). Several studies in the Northern Hemisphere showed that in warmer climate diabatic influence on the cyclone dynamics increases(Colle et al., 2013; Marciano et al., 2015; Michaelis et al., 2017). It is expected that with increased moisture availability in the atmosphere and increased air sea fluxes in a warmer climate (Yang et al., 2016, 2019), rainfall and wind associated with hybrid and warm core cyclones could become more intense.

Here we show that a RCM ensemble is able to reproduce the relative frequencies of occurrence of the different cyclone classes, and their main properties. Moreover, we investigate whether separating the cyclones in different classes by applying physically-based criteria related to the low pressure system's thermal structure provides added insight for the analysis of future changes of cyclone activity including the occurrence locations and associated impacts.

In Section 2 we describe the methodology and data used for the analysis, in Section 3 results on present and future cyclone activity are discussed, and conclusions are presented in Section 4.

## 2 Methods and Data

### 2.1 The climate model ensemble

Model data used in this study is obtained from regional climate model simulations performed in the NARCliM project (Evans et al., 2014). The 12 member model ensemble is a 4x3 matrix obtained using lateral boundary conditions obtained from four different CMIP3 global climate models (ECHAM5, CSIRO-Mk3.0, MIROC3.2 and CCMA3.1) and performing a dynamical downscaling using three versions of the regional climate model WRF differing in the model physics. Additional details on the different RCM choices of physics are provided in Supplementary Table S2. The RCM simulations have a horizontal resolution of 50 kms. Climate simulations based on the high emissions socio-economic scenario SRES A2 (IPCC, 2000) are analyzed, for two different 20-year time slices: 1990-2009 and 2060-2079.

The ability of the RCM ensemble to reproduce some of the features of cyclones in the region has been studied by Di Luca et al. (2016) and Pepler, Di Luca, et al. (2016).

Those studies showed that the properties of cyclones are generally well reproduced, while the internal variability has a larger sensitivity to the regional model than to the forcing global model. It was also shown that the feature of the cyclone climatology least well reproduced in model simulations is the seasonality, with an overestimation of the fraction of warm season events. Consequently, the key results of this study are presented individually for the warm (November-April) and cool (May-October) season, similar to previous studies (Di Luca et al., 2015; Pepler, Di Luca, et al., 2016).

The ERA-Interim reanalysis (Dee et al., 2011) at 0.75 ° horizontal resolution is used as a reference for the years 1979-2016. A downscaling of the NCEP/NCAR reanalysis from the NARCliM dataset is also used for 1990-2009.

### 2.2 Cyclone detection and classification

Cyclones are identified using a mean sea level pressure Laplacian-based detection scheme (Murray & Simmonds, 1991; Simmonds et al., 1999). The detection method and its implementation for the tracking of east Australian coast cyclones has been described in detail in Pepler et al. (2015). Pressure fields are re-gridded to a polar projection prior to tracking (equivalent to a 50 km horizontal resolution). The sensitivity of cyclone projections on the Laplacian detection scheme resolution was tested in a previous study (Pepler, Di Luca, et al., 2016), and was found not to have a strong impact on future cyclone trends. Following Pepler, Di Luca, et al. (2016), the numerical thresholds have been set to detect on average 22 cyclones per year, as reported in the observational database of Speer et al. (2009). In order to achieve that result, the minimum value of the pressure Laplacian is adjusted for each historical simulation. For climate projections, the same thresholds are used as in the historical simulation of each ensemble member.

Cyclones are classified as hybrid, cold core or warm core as described in detail in Cavicchia et al. (2019). The two thermal wind parameters defined in Hart (2003) are used at every time step to identify the cyclone's thermal core. A cyclone event is then classified as hybrid, cold core or warm core, if the majority of time steps in the cyclone track belongs to the respective class.

## 3 Results

### 3.1 Historical cyclones

The properties of Australian east coast cyclones in the RCM ensemble and ERA-Interim reanalysis are compared. Supplementary Table S1 shows the relative fraction of cyclones classified according to their prevailing dynamical classification. Compared to ERA-Interim, both the downscaled NCEP and the NARCliM ensemble tend to slightly underestimate the number of cold core cyclones and overestimate warm core and hybrid cyclones. The mismatch is larger in the cold season, when hybrid cyclones form 20% of systems in ERAI but more than 30% of cyclones in the downscaled NCEP simulations and the NARCliM ensemble mean. Supplementary Table 1 also shows the frequencies of the three cyclone dynamical classes in different ensemble subsets, respectively forced by different GCMs and using different RCMs for the downscaling. The relative occurrence of each type of cyclone is more sensitive to the RCM used than it is to the forcing GCM, with RCM2 the most similar to ERA-Interim.

Supplementary Figure S1 shows the seasonal cycle of different types of cyclones in the NARCliM ensemble mean compared with ERA-Interim and NCEP downscaling. Overall, there is a reasonable match between the reanalysis and RCM ensemble seasonal cycles. The reanalysis cold-core cyclones peak in the cold season is shifted towards the beginning of the warm season in both GCM-driven and reanalysis-driven RCMs simulations. There are consistently fewer cold season cold-core cyclones in the downscaled simulations than ERA-Interim (Supplementary Table 1), particularly around the transition to the warm season (August to October). The discrepancy in the seasonal cycles between cyclones detected in reanalysis and downscaled simulations results from a portion of the cold season cold core cyclones being represented as hybrid. This is likely due to small scale processes related to the RCM dynamics and convective parameterizations. The larger fraction of warm-core cyclones in the warm season and hybrid cyclones in May to October are on the other hand well matched between downscaled reanalysis and model simulations.

Supplementary Figure S2 shows cyclone track densities for the three different classes of cyclones for the RCM ensemble mean, and the zonally and meridional averaged track densities compared with the cyclones detected in ERA-Interim. Again, the model ensemble mean reproduces the main features of the spatial patterns of the different kinds of cyclones, including the meridionally- and zonally-averaged track densities. The differences between the model and reanalysis track densities mostly depend on the overall differences in the number of cyclones in each class, although there is a tendency towards fewer cyclones in NARCliM in the far south of the domain as well as more cold-core cyclones near the coast.

The thermal structure of hybrid cyclones suggests that, due to the thermal wind relation, they should be associated with stronger sustained low-level winds than cold-core cyclones. Figure 1 shows the composite 10-m wind speed and rainfall fields for all cyclones detected in ERA-Interim at the time of lowest central pressure. Hybrid cyclones have larger low-level wind speeds than cold-core cyclones in both the warm season (null hypothesis rejected in a Kolmogorov-Smirnov test for both the average and maximum wind speed in a 500 km radius) and the cold season (null hypothesis rejected in a K-S test for the maximum wind speed in a 500 km radius). The rainfall rates between the two classes of cyclones on the other hand do not appear to differ significantly (null hypothesis not rejected in a K-S test for either the average and maximum rainfall in a 500 km radius).

### 3.2 Climate projections

Relative changes in cyclone frequency between present and future simulations are shown in Fig. 2. The total number of cyclones decreases in future climate, consistent with findings of previous studies (Dowdy, Mills, Timbal, & Wang, 2013; Pepler, Di Luca, et al., 2016). The rate of decrease is about ten percent for cold-core cyclones, and around twenty percent for hybrid and warm-core cyclones. The ensemble spread of the decrease signal is, however, larger for warm-core than for hybrid cyclones. Pepler, Di Luca, et al. (2016) have shown that changes in cyclone activity in the cold season show a reduction signal in future climate that is consistent across most ensemble members and robust across different detection methodologies. Changes in the warm season were, on the other hand, found to be more sensitive to the detection scheme. Here we show that, all types of cyclones occurring in the cold season become less frequent, thus contributing to a robust overall decrease. Here and in the following we define a signal robust if at least 75% of the ensemble members agree on the sign of change. In the warm season, on the other hand, different kind of systems have contrasting signals, with cold core and warm core cyclones decreasing while hybrid cyclones show no clear change. For most classes of cyclones and seasons there is a good agreement between model ensemble members, with 75% or more of the simulations agreeing on the sign of change. One exception is the warm season hybrid cyclone frequency, whose change has a very large uncertainty, with the ensemble evenly split in models projecting an increased and decreased frequency. Supplementary table S4 shows the change in warm season hybrid cyclones number in every ensemble member. As the table shows, the uncertainty is driven by the GCMs, with all simulations forced by two out of four GCMs showing a positive change, and the simulations forced by the other GCMs showing a contrasting negative change.

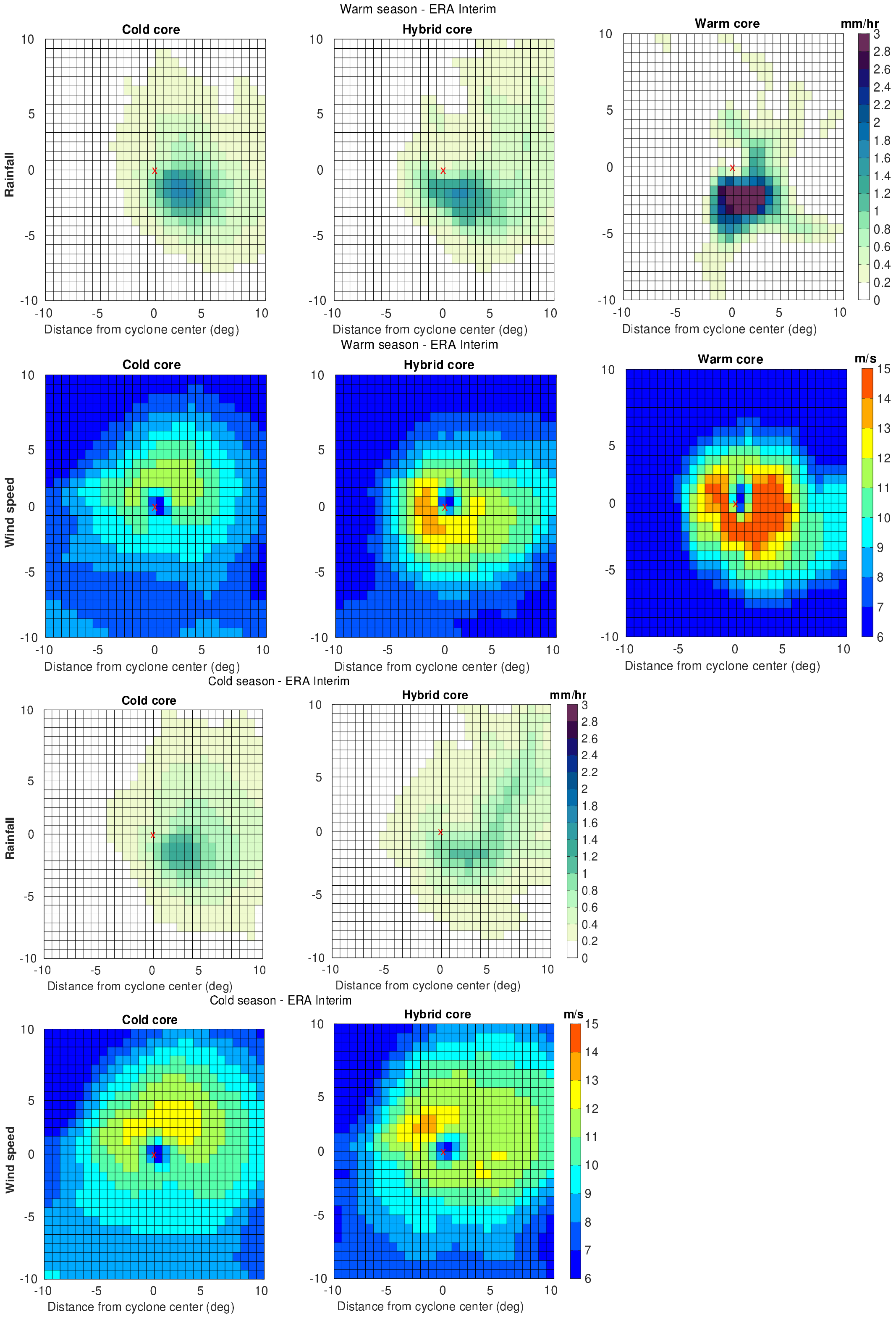

**Figure 1.** Composites of rainfall and 10-m wind speed fields at the time of the cyclone lowest central pressure for all cyclones detected in ERA-Interim.

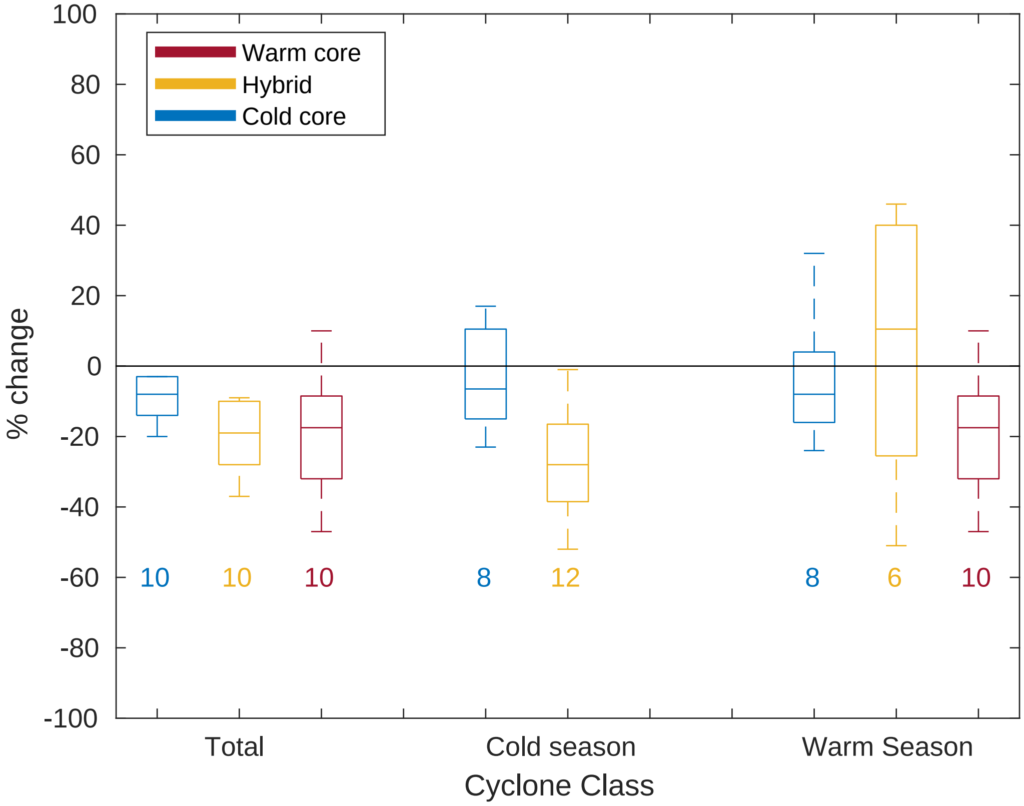

**Figure 2.** Box plot of relative changes of cyclone occurrence over the domain depicted in Fig. 3 between the historical (1990-2009) and future (2060-2079) periods in the A2 scenario, across the GCM-RCM ensemble, for respectively (left to right): the whole year, the cool season (May to October) and the warm season (November to April). Different cyclone classes are represented as indicated in the color legend. The boxes represent the interquartile range ($q_3 - q_1$). The central lines indicate the ensemble median values. The whiskers represent the most extreme data points in the range $q_{1,3} \pm 1.5 \times (q_3 - q_1)$. Outliers are not plotted. The numbers at the bottom show how many ensemble members agree on the sign of change.

Figure 3 shows changes in the track densities of different types of cyclones in different seasons. The year-round change of cold core cyclones track density shows a decrease in most locations, with a moderate increase in a smaller fraction of grid cells. The hybrid cyclone signal on the other hand has a different pattern, showing a dipole pattern with an increase in track density along the coast, and a decrease further offshore in the Tasman Sea. The projected signal is, however, only robust where the change is negative. In other words, for those models that project an increase of hybrid cyclones, such increase is mostly found to occur close to the Australian coast. Focusing on the seasonal signal, both cold core and hybrid cyclones show a mostly decreased frequency in the cold season. On the other hand, warm season track density changes of both cold-core and hybrid cyclones are mostly positive, with larger changes for hybrid cyclones and along the coast. Again, the signal is robust everywhere for the cold season, but only for areas away from the coast in the warm season. Concerning possible physical processes related to future changes in cyclone energy sources, we find, similarly to the result of Colle et al. (2013) for the Northern Hemisphere, that future changes in Eady growth rate are small (Supplementary Figure S3) but generally negative in the area of interest which could explain to some extent the decline in the frequency of cyclones. Consistent with Marciano et al. (2015) and Michaelis et al. (2017) we find, on the other hand, that future cyclones have enhanced latent heating (Supplementary Figure S4), pointing to an increasing diabatic influence.

As shown in Section 3.1, hybrid cyclones are associated with stronger low-level wind speeds than cold core cyclones. Assessing future changes in the rainfall and wind speed fields intensity and structure is therefore important information for disaster risk reduction and climate change adaptation strategies. Figure 4 and Supplementary Tables S8 and S9 show composite changes in the cyclone 10-m wind and rainfall fields for the different classes of cyclones and seasons. Large increases for hybrid and warm core cyclone rainfall are found in the warm season, while in the cold season only a moderate increase is found. For wind speed, a moderate increase of the maximum winds is found for hybrid cyclones in both seasons, while a larger increase is found for warm core cyclones. The changes in wind speed and rainfall are comparable in amplitude to those found in Michaelis et al. (2017) for the Northern Hemisphere.

## 4 Conclusions

In this paper, future changes in cyclone occurrence along the east coast of Australia were analyzed. A novel classification of low pressure systems according to their dynamical structure focusing on hybrid cyclones has been applied. The analysis builds upon previous studies on cyclones occurrence in a RCM ensemble (Pepler, Di Luca, et al., 2016), and shows that dividing cyclones into different classes leads to a clearer climate change signal. Changes in the year-round occurrence of cold-core and warm-core cyclones and of hybrid cyclones in the cold season are robust, in terms of the agreement between different models. Only for hybrid cyclones in the warm season there is a large remaining uncertainty. It is thus demonstrated that employing a physically-based classification of cyclones yields an added value in the understanding of future projections of these extreme weather events, by showing a clear signal for most types of cyclones.

Yearly values of future cyclone occurrence show a decreased frequency for all the classes of cyclones, with the rate of decrease ranging from about -10% for cold core cyclones to -20% for hybrid and warm core cyclones. Similar behavior appears in the cold season, with both cold core and hybrid cyclones decreasing in occurrence frequency, the decrease being larger for hybrid cyclones. In the warm season, in contrast, cold core and warm core cyclones both become less frequent, but hybrid cyclones become more frequent in the ensemble mean. However, the inter-ensemble spread is very large for warm season hybrid cyclones, with the number of simulations projecting an increase or a decrease of their frequency evenly split. The year-round cold core cyclone decrease signal is ho-

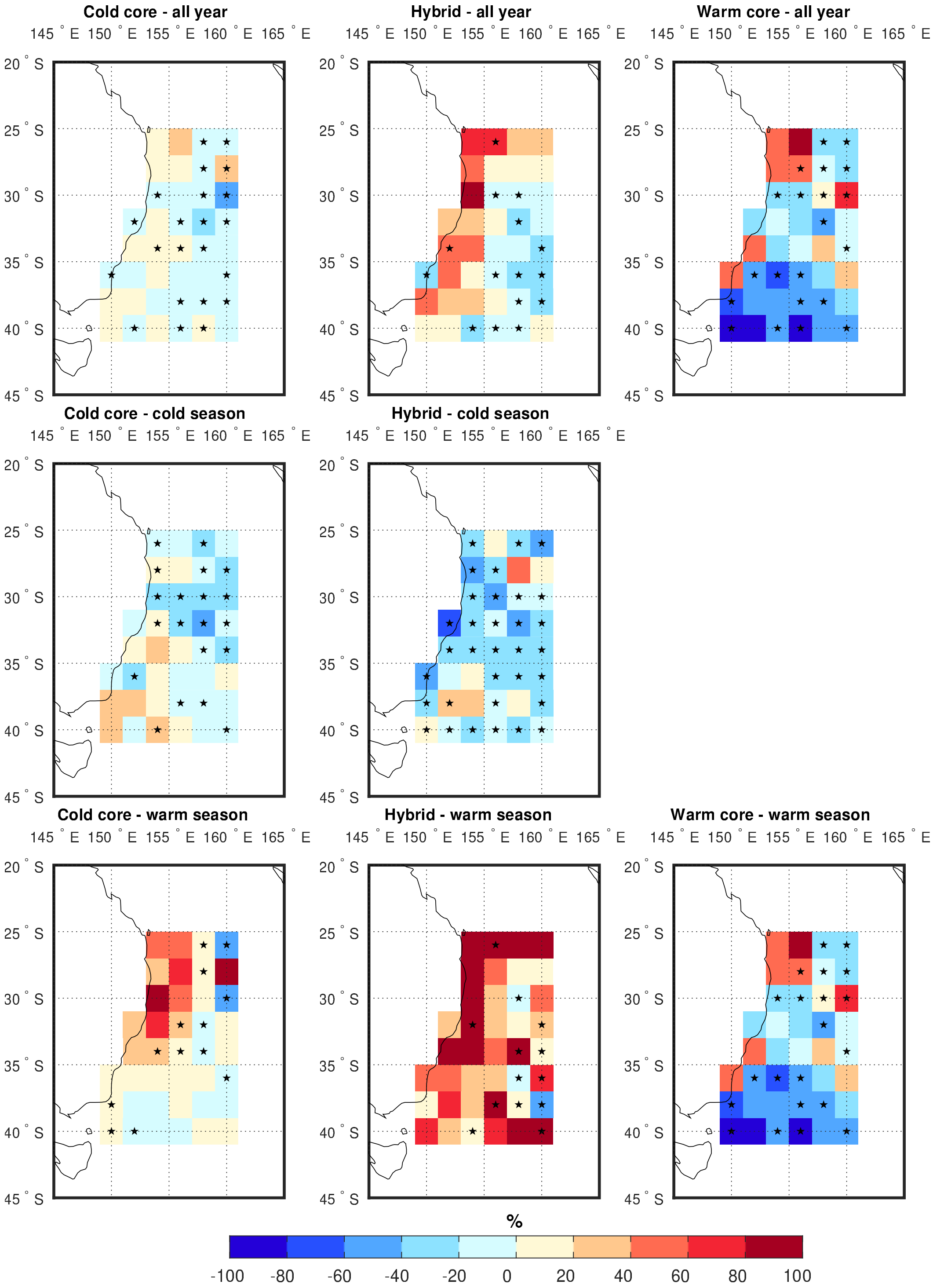

**Figure 3.** Relative changes in the cyclone track densities between the historical and future simulations, for different cyclone classes and seasons (as indicated in the panel titles). The relative change has been computed as $(TD_{fut} - TD_{pres})/TD_{pres}$, where $TD_{fut}$ and $TD_{pres}$ stand for track density in respectively future (2060-2079) and current (1990-2009) climate simulations. Stars indicate location where 75% or more of the ensemble members agree on the sign of change.

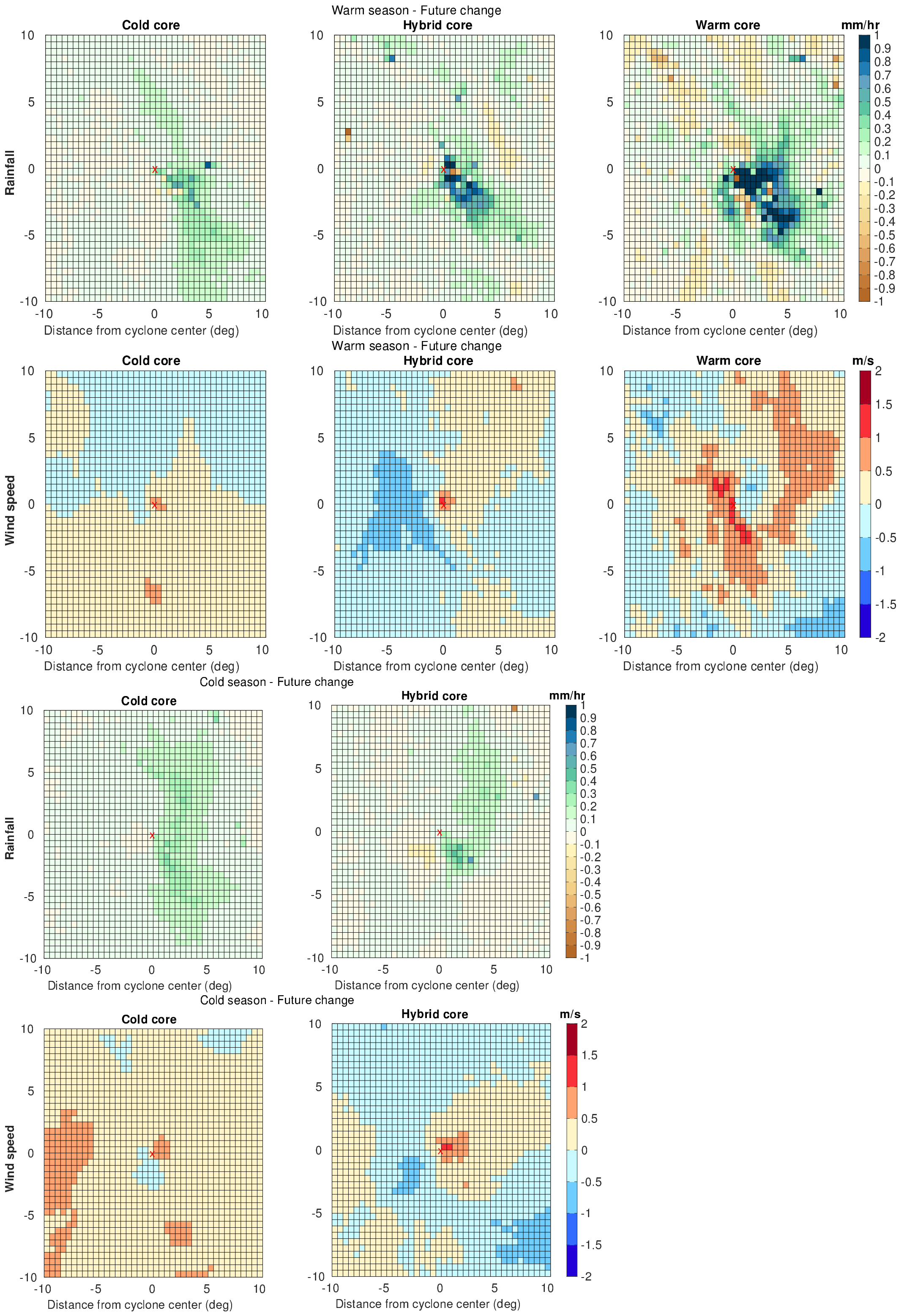

**Figure 4.** Composites at the time of the cyclone lowest central pressure of rainfall and 10-m wind speed fields change between future and historical simulations for all cyclones detected in NARCliM.

mogeneous in space, with most of the grid points in the region of interest registering a negative sign of change for storms track density. Hybrid cyclone track density, on the other hand, shows a year-round increase closer to the coast, and a decrease farther off in the ocean. The coastal increase, however, is not a robust signal, with less than 75% of the simulations agreeing on the sign of the change. This finding is consistent with the results of Pepler, Alexander, et al. (2016) who found that the intensification of the warm East Australian Current in regional model simulations resulted in an increased likelihood of the subtropical/hybrid systems and of the systems with less favorable upper tropospheric conditions. This suggests that the projected increase in warm season hybrid cyclones near the east coast could be a result of the projected intensification of the East Australian Current during the 21st century (Oliver et al., 2014) counterbalancing decreases in baroclinicity and cold core cyclones. Furthermore, although sea surface temperatures are increasing and studies indicate a long-term climate change trend towards an expanding tropics (Lu et al., 2007; Lucas & Nguyen, 2015), the projections for this region indicate a future change towards fewer warm core cyclones based on this analysis. Cold season cold-core cyclone activity shows a larger decrease in the northern part of the domain with respect to the southern part, consistent with previous findings on future poleward displacement of the Southern Hemisphere storm track (Bengtsson et al., 2006).

Hybrid cyclones are found to have stronger winds than cold core cyclones in all seasons in the historical period. Therefore, understanding future changes in hybrid cyclones activity is an important information for adaptation purposes. In future projections, a further moderate increase in hybrid cyclone wind speed is found. On the other hand, rainfall associated with hybrid cyclones in the warm season is projected to increase by a large amount (up to a 30% increase for locations poleward of the cyclone center). The implications of increased rainfall and a potential increase of hybrid cyclones activity are highly relevant for the impacts on densely populated coastal areas, due to changes in flooding risk (Dowdy et al., 2019).

The analysis shows that a physically-based classification applied to a regional climate model ensemble addresses key knowledge gaps in the understanding of future changes of hybrid cyclones occurrence along the Australian East coast (Dowdy et al., 2019). New knowledge includes a better understanding of future changes in the warm season, including changes in hybrid cyclone occurrence close to the coast that would have important implications for the affected regions due to the associated impacts. The results suggest this methodology can be used to analyze future changes in hybrid cyclone occurrence in several other regions in the world (Yanase et al., 2014; da Rocha et al., 2018). Future work will investigate in depth the sources of uncertainty for the warm season hybrid cyclones projections.

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## References

Bengtsson, L., Hodges, K. I., & Roeckner, E. (2006). Storm tracks and climate change. *J. Climate*, *19*, 3518–3543.

Callaghan, J., & Power, S. B. (2014). Major coastal flooding in southeastern Australia 1860–2012, associated deaths and weather systems. *Aust. Meteor. Ocean. J.*, *64*, 183–213.

Cavicchia, L., Dowdy, A., & Walsh, K. (2018). Energetics and dynamics of subtropical Australian east coast cyclones: two contrasting cases. *Mon. Wea. Rev.*, *146*, 1511–1525.

Cavicchia, L., Pepler, A., Dowdy, A., & Walsh, K. (2019). A physically based climatology of the occurrence and intensification of Australian east coast lows. *J. Climate*, *32*, 2823–2841.

Colle, B. A., Zhang, Z., Lombardo, K. A., Chang, E., Liu, P., & Zhang, M. (2013). Historical evaluation and future prediction of eastern North American and western Atlantic extratropical cyclones in the CMIP5 models during the cool season. *J. Climate*, *26*, 6882–6903.

da Rocha, R. P., Reboita, M. S., Gozzo, L. F., Dutra, L. M. M., & de Jesus, E. M. (2018). Subtropical cyclones over the oceanic basins: A review. *Ann. N.Y. Acad. Sci.*, *1436*, 138–156.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., … Vitart, F. (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, *137*, 553–597.

Di Luca, A., Evans, J. P., Pepler, A., Alexander, L., & Argüeso, D. (2015). Resolution sensitivity of cyclone climatology over eastern Australia using six reanalysis products. *J. Climate*, *28*, 9530–9549.

Di Luca, A., Evans, J. P., Pepler, A. S., Alexander, L., & Argüeso, D. (2016). Evaluating the representation of Australian east coast lows in a regional climate model ensemble. *J. South. Hemisphere Earth. Syst. Sci.*, *66*, 108–124.

Dowdy, A. J., Mills, G. A., & Timbal, B. (2013). Large-scale diagnostics of extratropical cyclogenesis in eastern Australia. *Int. J. Climatol.*, *33*, 2318–2327.

Dowdy, A. J., Mills, G. A., Timbal, B., & Wang, Y. (2013). Changes in the risk of extratropical cyclones in eastern Australia. *J. Climate*, *26*, 1403–1417.

Dowdy, A. J., Pepler, A., Di Luca, A., Cavicchia, L., Mills, G., Evans, J. P., … Walsh, K. (2019). Review of australian east coast low pressure systems and associated extremes. *Climate Dyn.*, 1–24. doi: 10.1007/s00382-019-04836-8

Evans, J., Ji, F., Lee, C., Smith, P., Argüeso, D., & Fita, L. (2014). Design of a regional climate modelling projection ensemble experiment–NARCliM. *Geosci. Model Dev.*, *7*, 621–629.

Garde, L. A., Pezza, A. B., & Bye, J. A. T. (2010). Tropical transition of the 2001 Australian Duck. *Mon. Wea. Rev.*, *138*, 2038–2057.

Hart, R. E. (2003). A cyclone phase space derived from thermal wind and thermal asymmetry. *Mon. Wea. Rev.*, *131*, 585–616.

IPCC. (2000). *Special report on emissions scenarios (SRES), a special report of Working Group III of the intergovernmental panel on climate change.* Cambridge University Press, Cambridge.

Ji, F., Evans, J. P., Argueso, D., Fita, L., & Di Luca, A. (2015). Using large-scale diagnostic quantities to investigate change in East Coast Lows. *Climate Dyn.*, *45*, 2443–2453.

Lu, J., Vecchi, G. A., & Reichler, T. (2007). Expansion of the hadley cell under global warming. *Geophys. Res. Lett.*, *34*.

Lucas, C., & Nguyen, H. (2015). Regional characteristics of tropical expansion and the role of climate variability. *J. Geophys. Res.: Atmos.*, *120*, 6809–6824.

Marciano, C. G., Lackmann, G. M., & Robinson, W. A. (2015). Changes in US East Coast cyclone dynamics with climate change. *J. Climate*, *28*, 468–484.

Michaelis, A. C., Willison, J., Lackmann, G. M., & Robinson, W. A. (2017). Changes in winter North Atlantic extratropical cyclones in high-resolution regional pseudo–global warming simulations. *J. Climate*, *30*, 6905–6925.

Mills, G. A., Webb, R., Davidson, N. E., Kepert, J., Seed, A., & Abbs, D. (2010). *The Pasha Bulker east coast low of 8 June 2007* (Vol. 23; Centre for Australian Weather and Climate Research Tech. Rep.) ([Available online at `www.cawcr.gov.au/technical-reports/CTR_023.pdf`])

Murray, R. J., & Simmonds, I. (1991). A numerical scheme for tracking cyclone centres from digital data. *Aust. Meteorol. Mag.*, *39*, 155–166.

Oliver, E. C., Wotherspoon, S. J., Chamberlain, M. A., & Holbrook, N. J. (2014). Projected tasman sea extremes in sea surface temperature through the twenty-first century. *J. Climate*, *27*, 1980–1998.

Pepler, A. S., Alexander, L. V., Evans, J. P., & Sherwood, S. C. (2016). The influence of local sea surface temperatures on Australian east coast cyclones. *J. Geophys. Res.: Atmos.*, *121*, 352–363.

Pepler, A. S., Di Luca, A., Ji, F., Alexander, L. V., Evans, J. P., & Sherwood, S. C. (2015). Impact of identification method on the inferred characteristics and variability of Australian East Coast Lows. *Mon. Wea. Rev.*, *143*, 864–877.

Pepler, A. S., Di Luca, A., Ji, F., Alexander, L. V., Evans, J. P., & Sherwood, S. C. (2016). Projected changes in east Australian midlatitude cyclones during the 21st century. *Geophys. Res. Lett.*, *43*, 334–340.

Pepler, A. S., & Rakich, C. S. (2010). Extreme inflow events and synoptic forcing in Sydney catchments. In *Iop conference series: Earth and environmental science* (Vol. 11, p. 012010).

Pezza, A. B., Garde, L. A., Veiga, J. A. P., & Simmonds, I. (2014). Large scale features and energetics of the hybrid subtropical low Duck over the Tasman Sea. *Climate Dyn.*, *42*, 453–466.

Power, S. B., & Callaghan, J. (2016). Variability in severe coastal flooding, associated storms, and death tolls in southeastern Australia since the mid–nineteenth century. *Journal of Applied Meteorology and Climatology*, *55*, 1139–1149.

Quinting, J. F., Catto, J. L., & Reeder, M. J. (2019). Synoptic climatology of hybrid cyclones in the australian region. *Quart. J. Roy. Meteor. Soc.*, *145*, 288–302.

Simmonds, I., Murray, R. J., & Leighton, R. M. (1999). A refinement of cyclone tracking methods with data from FROST. *Aust. Meteor. Mag.*, Special Edition, 35–49. ([Available online at `http://www.bom.gov.au/jshess/docs/1999/simmonds.pdf`])

Speer, M. S., Wiles, P., Pepler, A., et al. (2009). Low pressure systems off the New South Wales coast and associated hazardous weather: establishment of a database. *Aust. Meteorol. Ocean. J.*, *58*, 29–39.

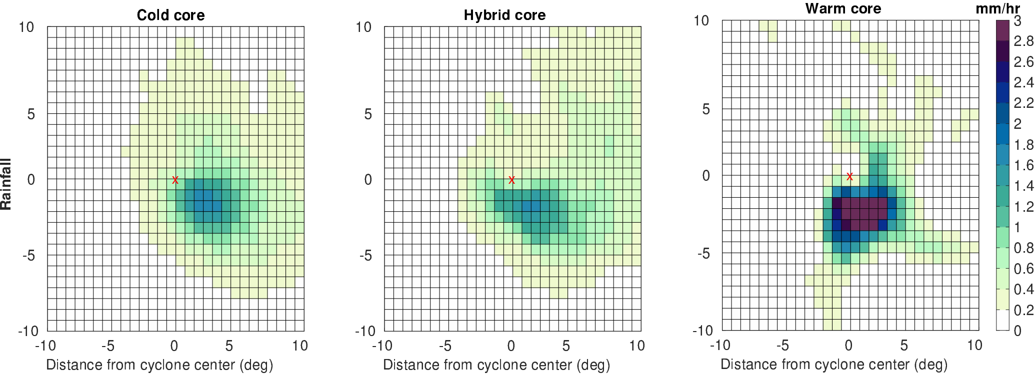
Yanase, W., Niino, H., Hodges, K., & Kitabatake, N. (2014). Parameter spaces of environmental fields responsible for cyclone development from tropics to extratropics. *J. Climate*, *27*, 652–671.

Yang, H., Lohmann, G., Shi, X., & Li, C. (2019). Enhanced mid-latitude meridional heat imbalance induced by the ocean. *Atmosphere*, *10*(12), 746.

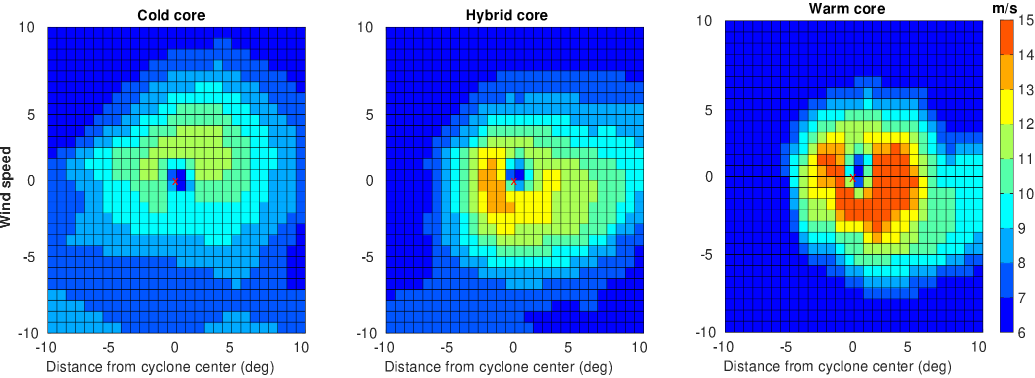
Yang, H., Lohmann, G., Wei, W., Dima, M., Ionita, M., & Liu, J. (2016). Intensification and poleward shift of subtropical western boundary currents in a warming climate. *J. Geophys. Res.: Oceans*, *121*(7), 4928–4945.

**Figure 1.**

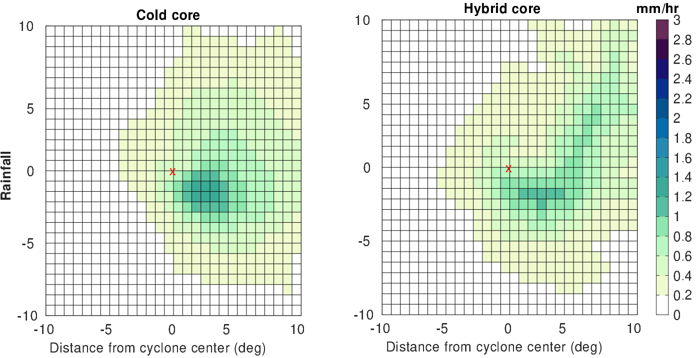
Warm season - ERA Interim



Warm season - ERA Interim



Cold season - ERA Interim



Cold season - ERA Interim

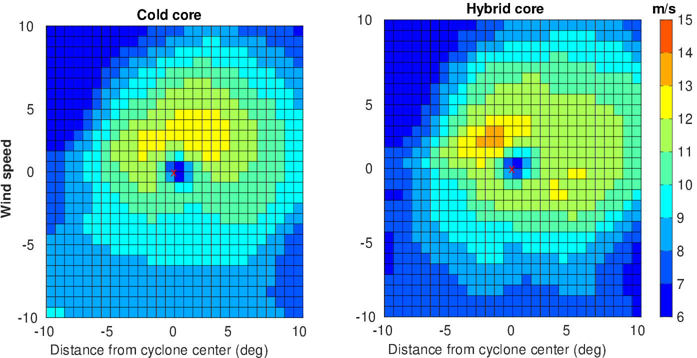


**Figure 2.**

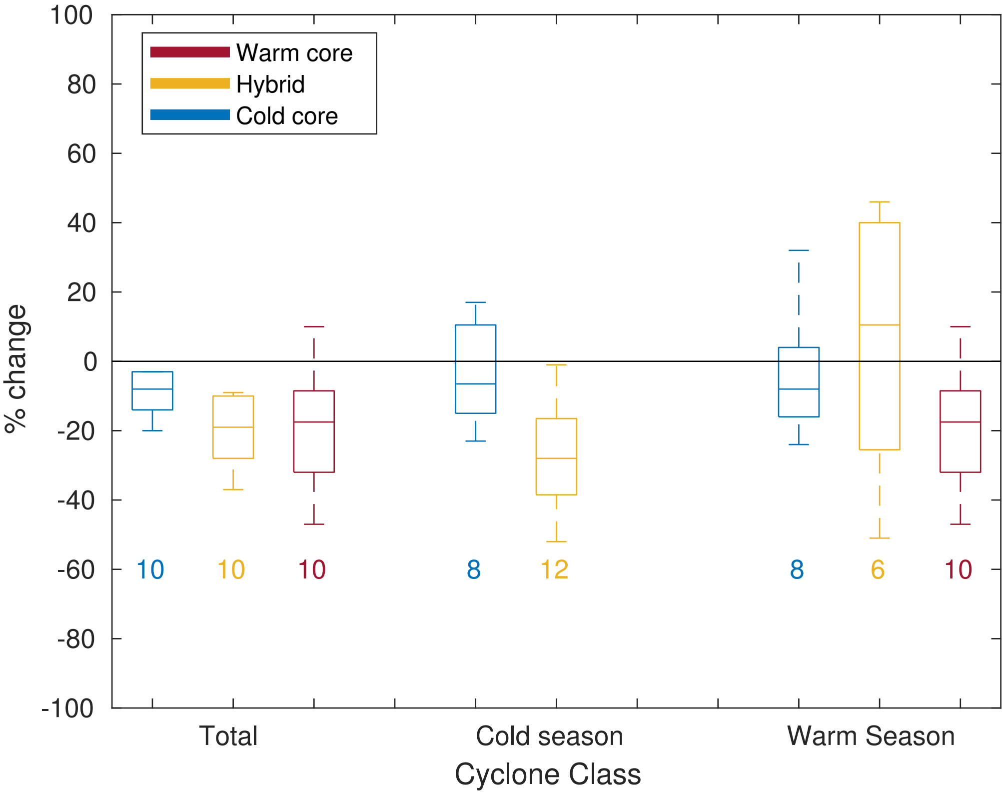

Warm core
Hybrid
Cold core
100
80
60
40
20
0
-20
-40
-60
-80
-100
% change
10
10
10
8
12
8
6
10
Total
Cold season
Warm Season
Cyclone Class

**Figure 3.**

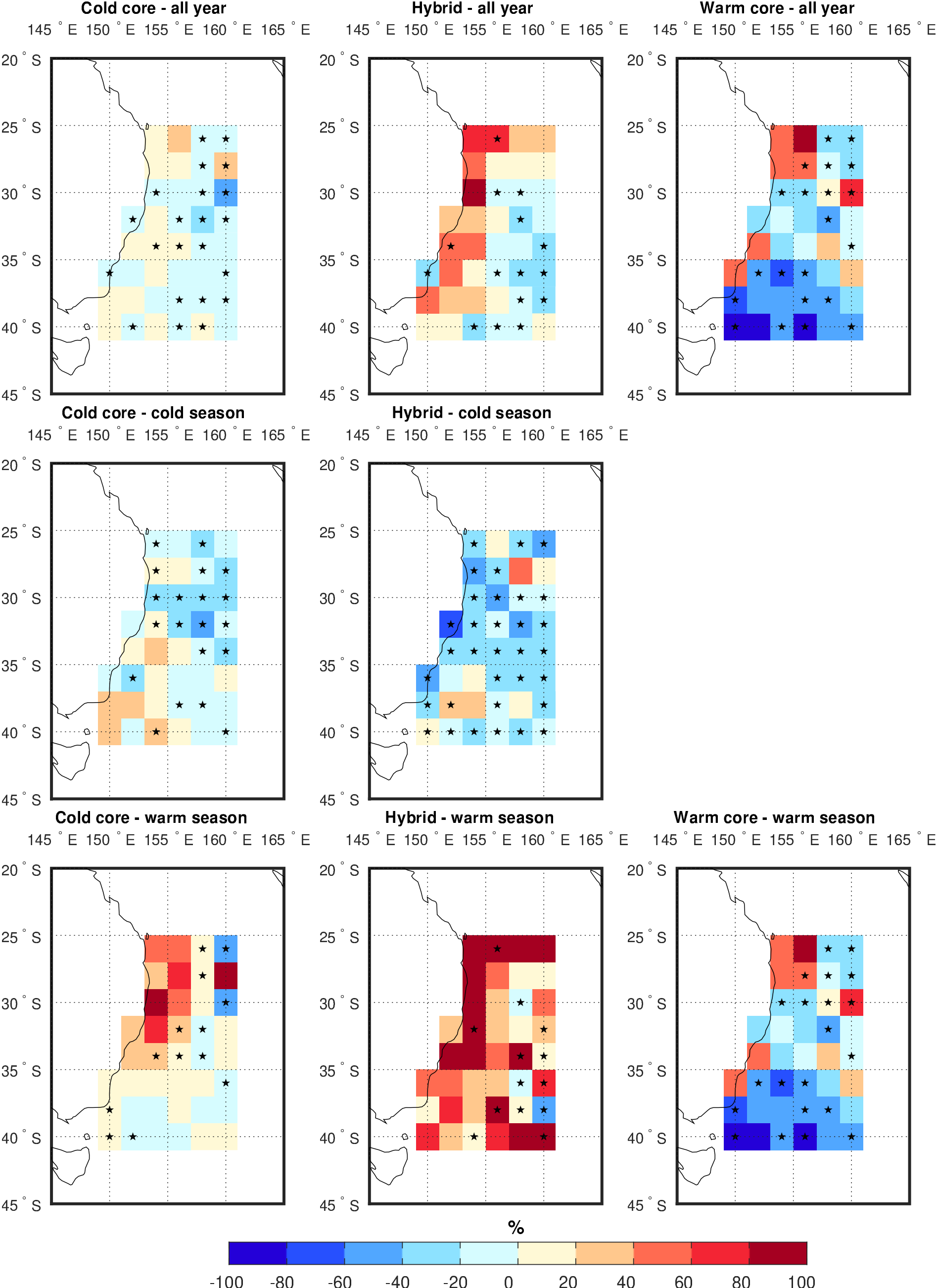
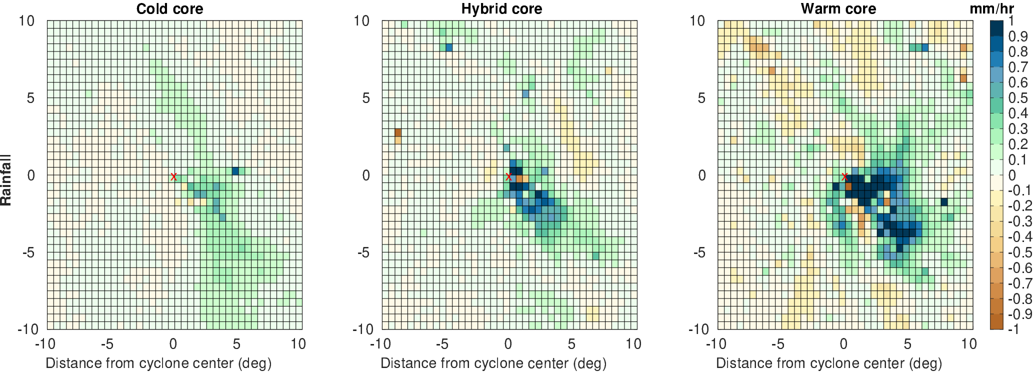
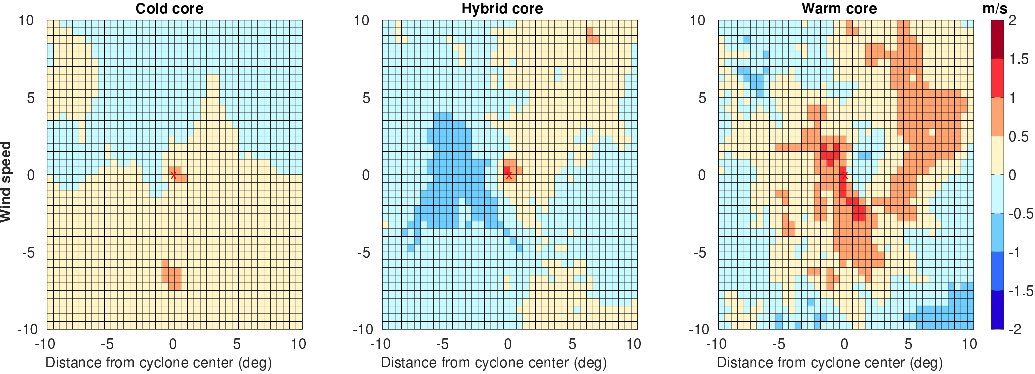

Cold core - all year
Hybrid - all year
Warm core - all year
Cold core - cold season
Hybrid - cold season
Cold core - warm season
Hybrid - warm season
Warm core - warm season
145 °E
150 °E
155 °E
160 °E
165 °E
20 °S
25 °S
30 °S
35 °S
40 °S
45 °S
%
-100
-80
-60
-40
-20
0
20
40
60
80
100

**Figure 4.**

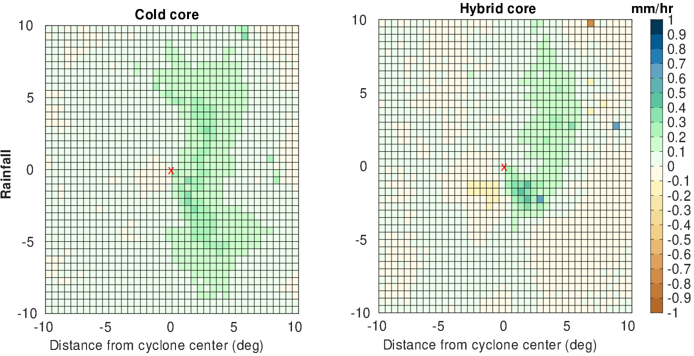
Warm season - Future change



Warm season - Future change



Cold season - Future change



Cold season - Future change