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

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8 **Key Points:**

- 9
- 10 • A physically-based classification of hybrid cyclones is applied to an ensemble of regional climate model simulations.
 - 11 • The cyclone classification method adds value to the projections of future cyclone activity, making them more robust.
 - 12 • Results indicate future changes (2060-2079) towards more intense impacts associated with hybrid cyclones.
- 13
- 14

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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).

63 A more recent study (Pepler, Di Luca, et al., 2016) based on an ensemble of regional cli-
64 mate models (RCM) and comparing different detection methods found a seasonality in
65 the cyclone activity climate change signal, with the cold season characterized by a ro-
66 bust decrease, while the warm season shows a much larger uncertainty in the response
67 to climate drivers. It was found moreover that there is a low agreement among the en-
68 semble members on the changes of cyclone activity at different location within the re-
69 gion, hindering the assessment of possible changes of cyclone impacts.

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

79 The Australian east coast is one of the regions characterized by the occurrence of
80 cyclones with hybrid features (Garde et al., 2010; Pezza et al., 2014; Cavicchia et al., 2018).
81 It has been estimated that between a third and one half of all cyclones forming in the
82 region have prevailing or partial hybrid features (Cavicchia et al., 2019; Quinting et al.,
83 2019). Several studies in the Northern Hemisphere showed that in warmer climate di-
84 abatic influence on the cyclone dynamics increases (Colle et al., 2013; Marciano et al.,
85 2015; Michaelis et al., 2017). It is expected that with increased moisture availability in
86 the atmosphere and increased air sea fluxes in a warmer climate (Yang et al., 2016, 2019),
87 rainfall and wind associated with hybrid and warm core cyclones could become more in-
88 tense.

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

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

98 **2 Methods and Data**

99 **2.1 The climate model ensemble**

100 Model data used in this study is obtained from regional climate model simulations
101 performed in the NARClIM project (Evans et al., 2014). The 12 member model ensem-
102 ble is a 4x3 matrix obtained using lateral boundary conditions obtained from four dif-
103 ferent CMIP3 global climate models (ECHAM5, CSIRO-Mk3.0, MIROC3.2 and CCMA3.1)
104 and performing a dynamical downscaling using three versions of the regional climate model
105 WRF differing in the model physics. Additional details on the different RCM choices of
106 physics are provided in Supplementary Table S2. The RCM simulations have a horizon-
107 tal resolution of 50 kms. Climate simulations based on the high emissions socio-economic
108 scenario SRES A2 (IPCC, 2000) are analyzed, for two different 20-year time slices: 1990-
109 2009 and 2060-2079.

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

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

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

122 2.2 Cyclone detection and classification

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

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

140 3 Results

141 3.1 Historical cyclones

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

154 Supplementary Figure S1 shows the seasonal cycle of different types of cyclones in
155 the NARClIM ensemble mean compared with ERA-Interim and NCEP downscaling. Over-
156 all, there is a reasonable match between the reanalysis and RCM ensemble seasonal cy-
157 cles. The reanalysis cold-core cyclones peak in the cold season is shifted towards the be-
158 ginning of the warm season in both GCM-driven and reanalysis-driven RCMs simula-
159 tions. There are consistently fewer cold season cold-core cyclones in the downscaled sim-

160 ulations than ERA-Interim (Supplementary Table 1), particularly around the transition
161 to the warm season (August to October). The discrepancy in the seasonal cycles between
162 cyclones detected in reanalysis and downscaled simulations results from a portion of the
163 cold season cold core cyclones being represented as hybrid. This is likely due to small
164 scale processes related to the RCM dynamics and convective parameterizations. The larger
165 fraction of warm-core cyclones in the warm season and hybrid cyclones in May to Oc-
166 tober are on the other hand well matched between downscaled reanalysis and model sim-
167 ulations.

168 Supplementary Figure S2 shows cyclone track densities for the three different classes
169 of cyclones for the RCM ensemble mean, and the zonally and meridional averaged track
170 densities compared with the cyclones detected in ERA-Interim. Again, the model en-
171 semble mean reproduces the main features of the spatial patterns of the different kinds
172 of cyclones, including the meridionally- and zonally-averaged track densities. The dif-
173 ferences between the model and reanalysis track densities mostly depend on the over-
174 all differences in the number of cyclones in each class, although there is a tendency to-
175 wards fewer cyclones in NARClIM in the far south of the domain as well as more cold-
176 core cyclones near the coast.

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

188 3.2 Climate projections

189 Relative changes in cyclone frequency between present and future simulations are
190 shown in Fig. 2. The total number of cyclones decreases in future climate, consistent with
191 findings of previous studies (Dowdy, Mills, Timbal, & Wang, 2013; Pepler, Di Luca, et
192 al., 2016). The rate of decrease is about ten percent for cold-core cyclones, and around
193 twenty percent for hybrid and warm-core cyclones. The ensemble spread of the decrease
194 signal is, however, larger for warm-core than for hybrid cyclones. Pepler, Di Luca, et al.
195 (2016) have shown that changes in cyclone activity in the cold season show a reduction
196 signal in future climate that is consistent across most ensemble members and robust across
197 different detection methodologies. Changes in the warm season were, on the other hand,
198 found to be more sensitive to the detection scheme. Here we show that, all types of cy-
199 clones occurring in the cold season become less frequent, thus contributing to a robust
200 overall decrease. Here and in the following we define a signal robust if at least 75% of
201 the ensemble members agree on the sign of change. In the warm season, on the other hand,
202 different kind of systems have contrasting signals, with cold core and warm core cyclones
203 decreasing while hybrid cyclones show no clear change. For most classes of cyclones and
204 seasons there is a good agreement between model ensemble members, with 75% or more
205 of the simulations agreeing on the sign of change. One exception is the warm season hy-
206 brid cyclone frequency, whose change has a very large uncertainty, with the ensemble evenly
207 split in models projecting an increased and decreased frequency. Supplementary table
208 S4 shows the change in warm season hybrid cyclones number in every ensemble mem-
209 ber. As the table shows, the uncertainty is driven by the GCMs, with all simulations forced
210 by two out of four GCMs showing a positive change, and the simulations forced by the
211 other GCMs showing a contrasting negative change.

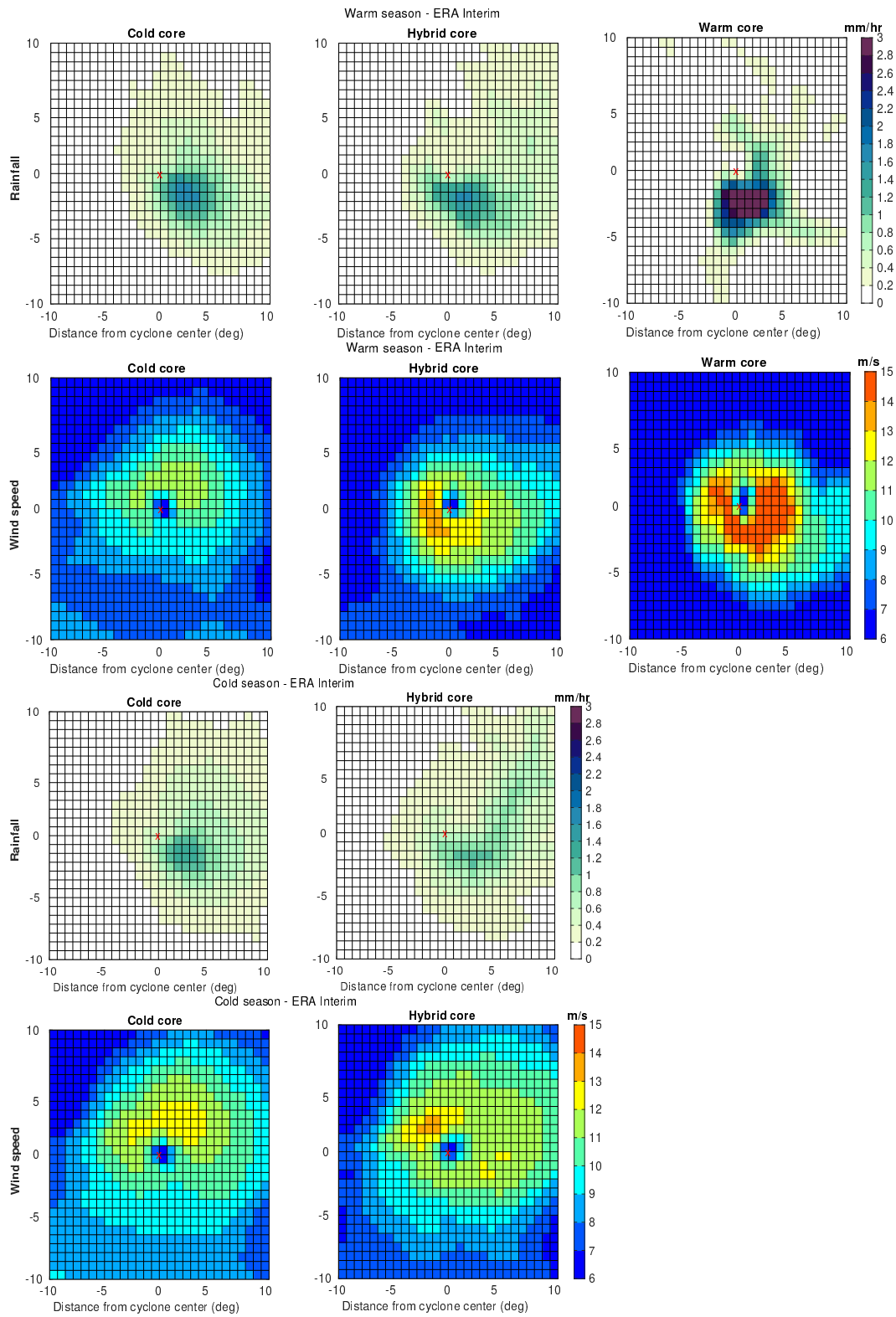


Figure 1. Composites of rainfall and 10-m wind speed fields at the time of the cyclone lowest central pressure for all cyclones detected in ERA-Interim.

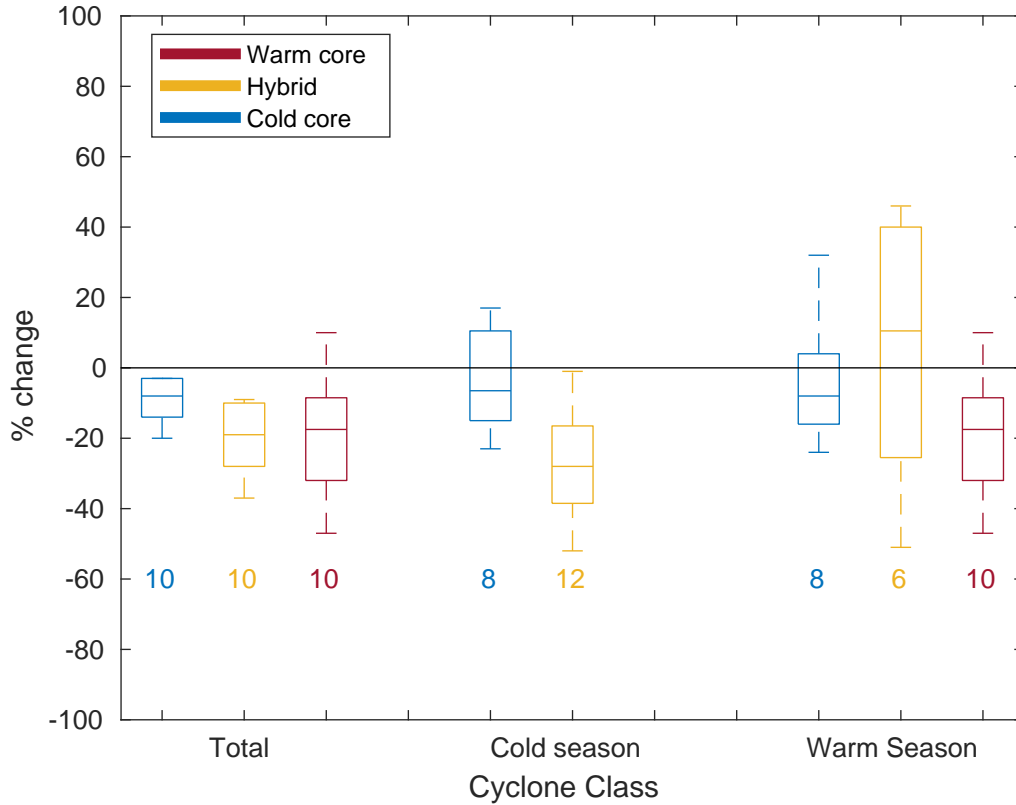


Figure 2. Box plot of relative changes of cyclone occurrence over the domain depicted in Fig. 3 between the historical (1990-2009) and future (2060-2079) periods in the A2 scenario, across the GCM-RCM ensemble, for respectively (left to right): the whole year, the cool season (May to October) and the 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-

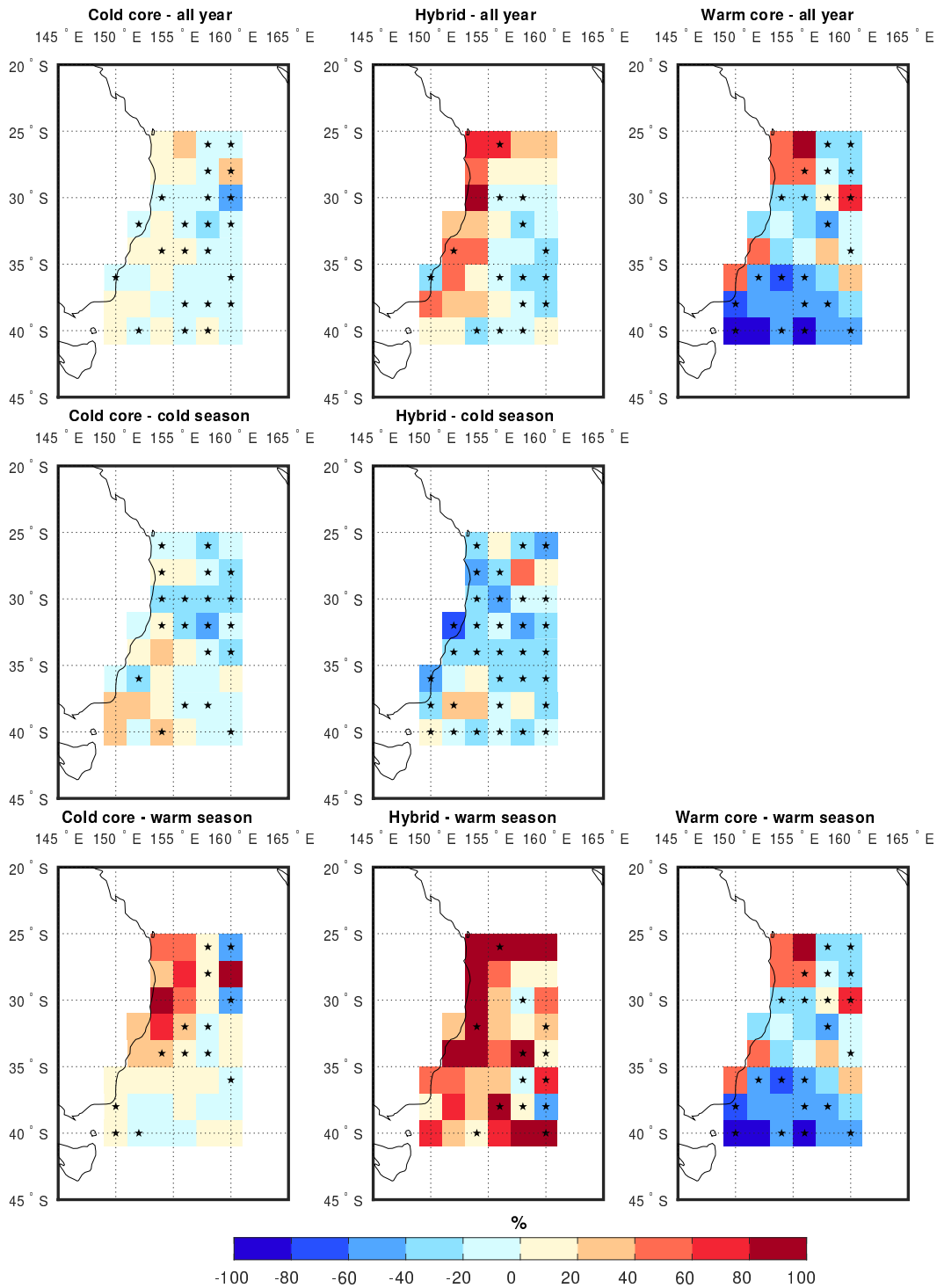


Figure 3. Relative changes in the cyclone track densities between the historical and future simulations, for different cyclone classes and seasons (as indicated in the panel titles). The relative change has been computed as $(TD_{fut} - TD_{pres})/TD_{pres}$, where TD_{fut} and TD_{pres} stand for track 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.

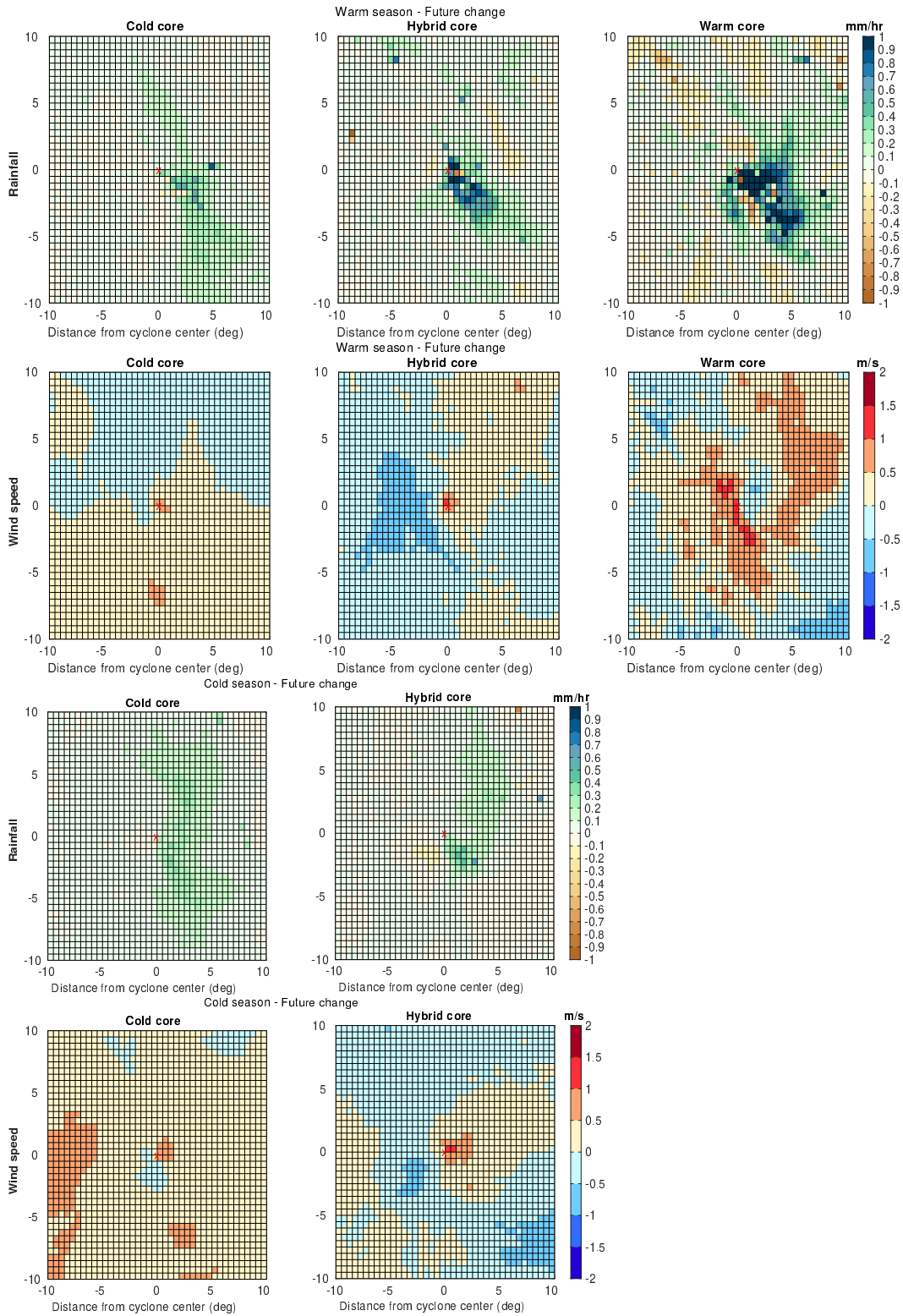


Figure 4. Composites at the time of the cyclone lowest central pressure of rainfall and 10-m wind speed fields change between future and historical simulations for all cyclones detected in NARClM.

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

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

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

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306 data used in the analysis is available on a public repository: dx.doi.org/10.26188/5e4b3a9a66754.

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Figure 1.

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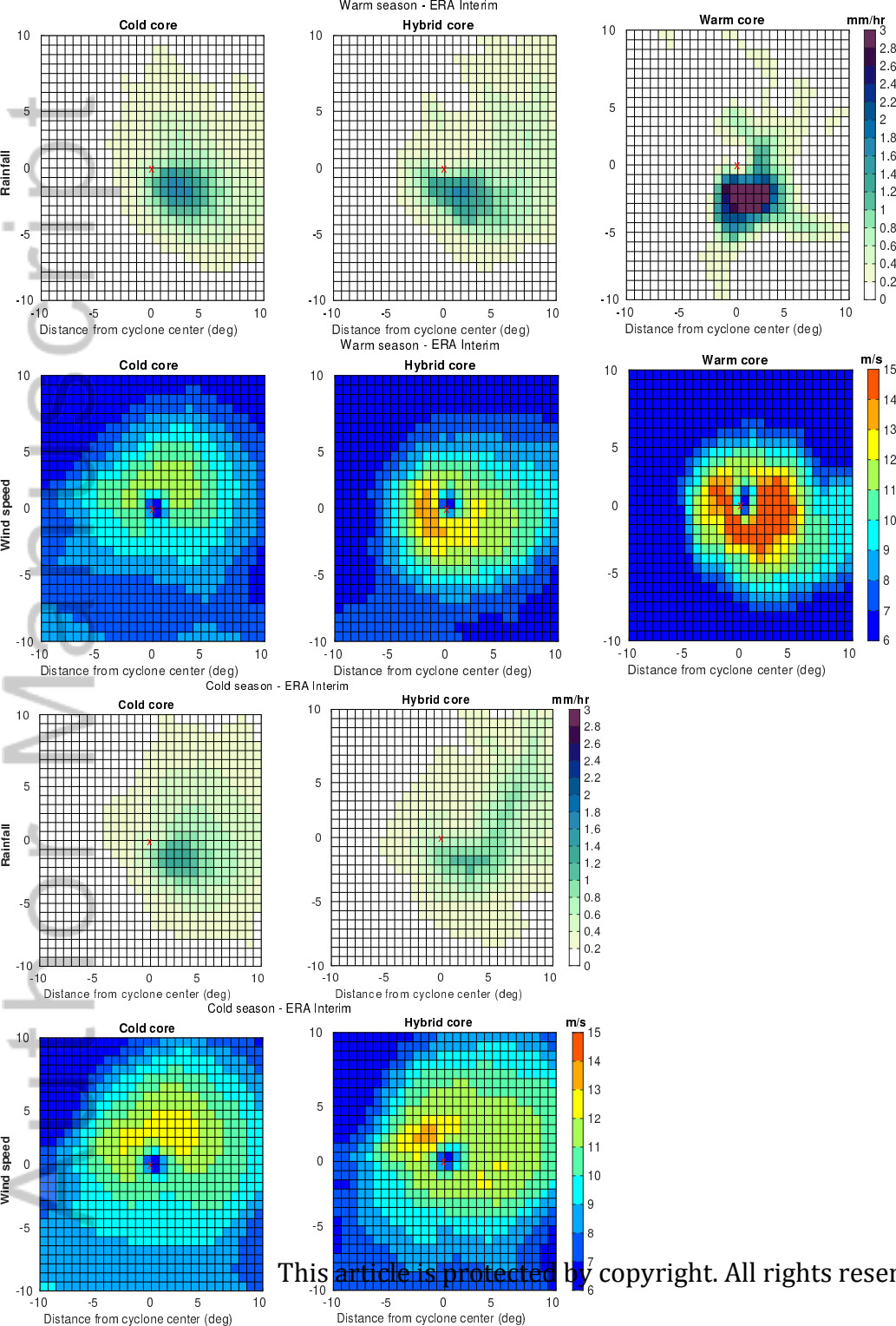


Figure 2.

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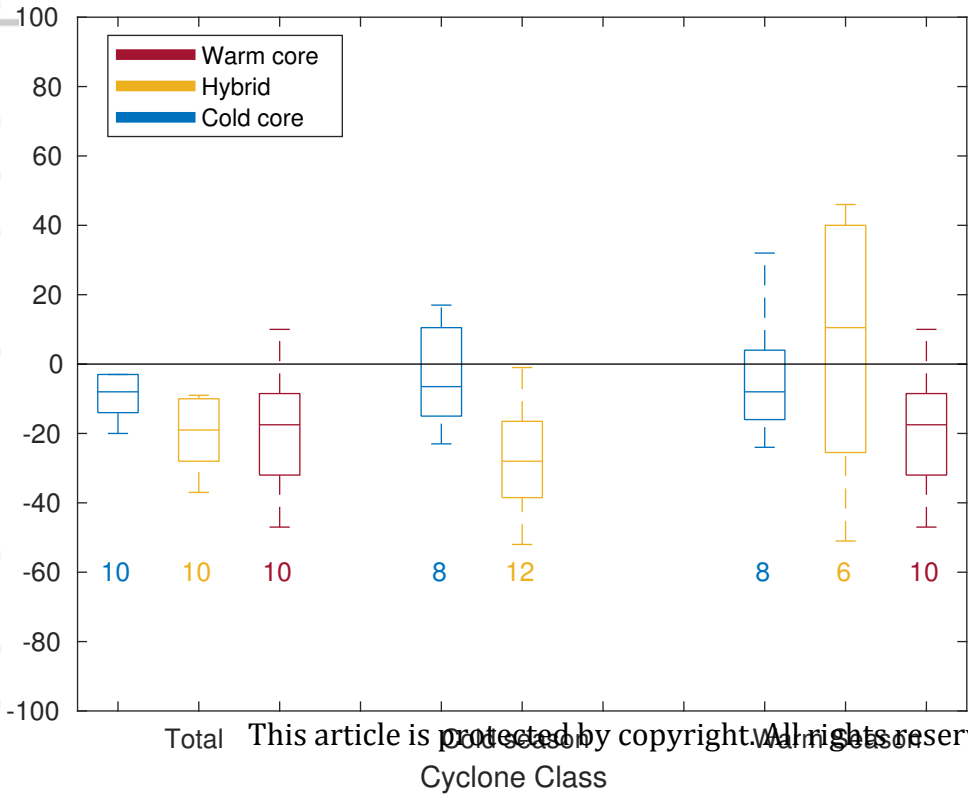


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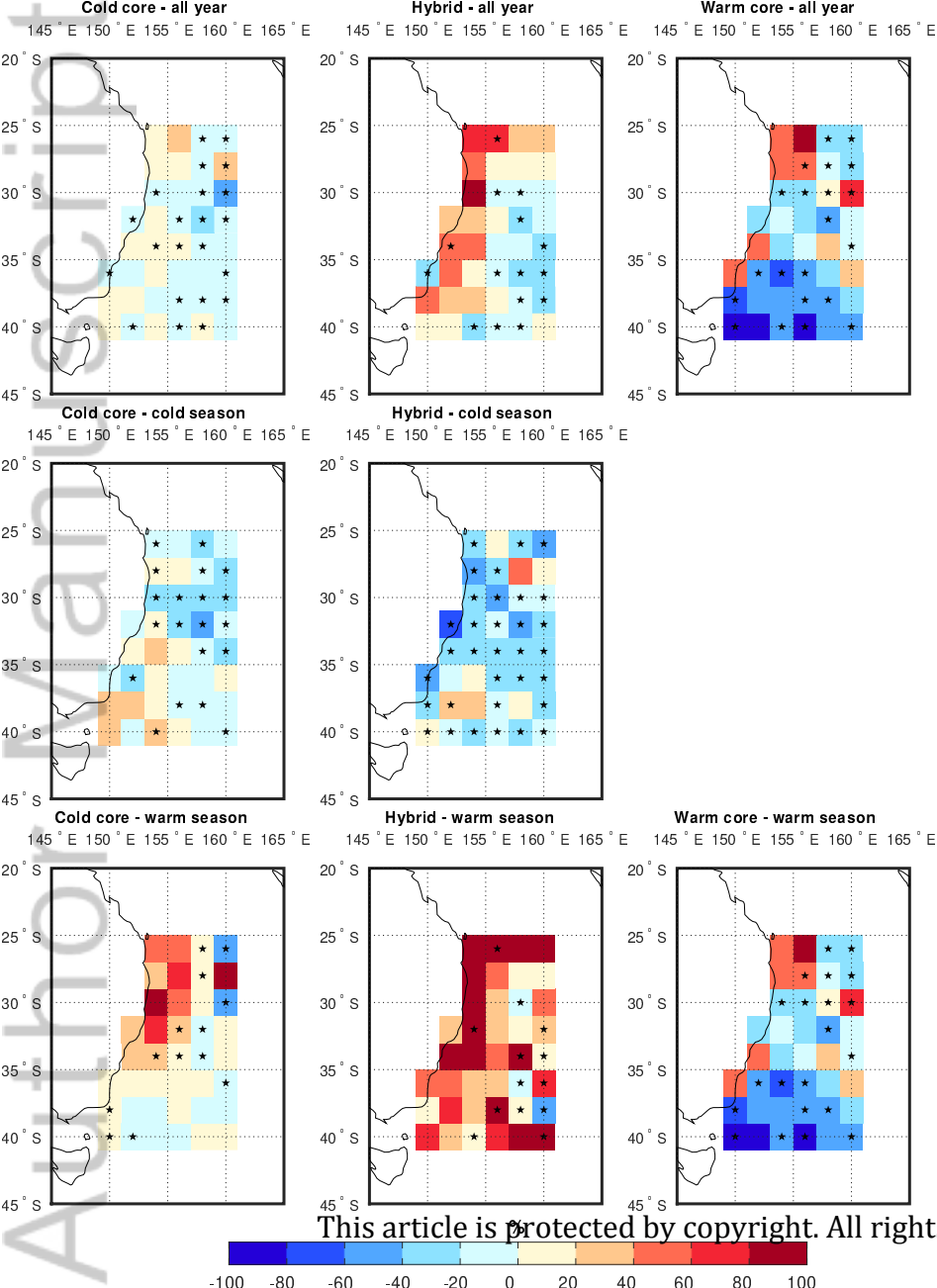
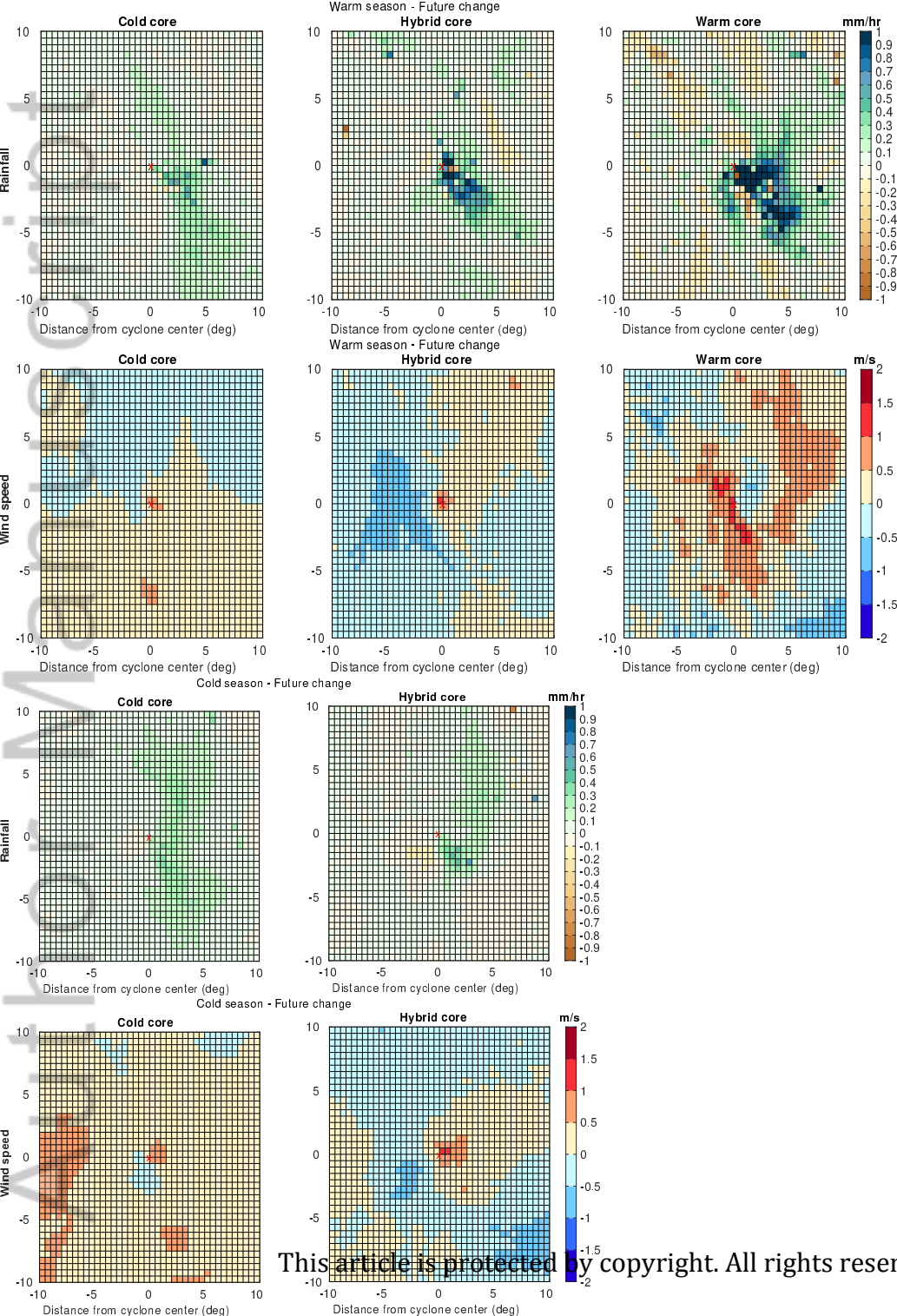
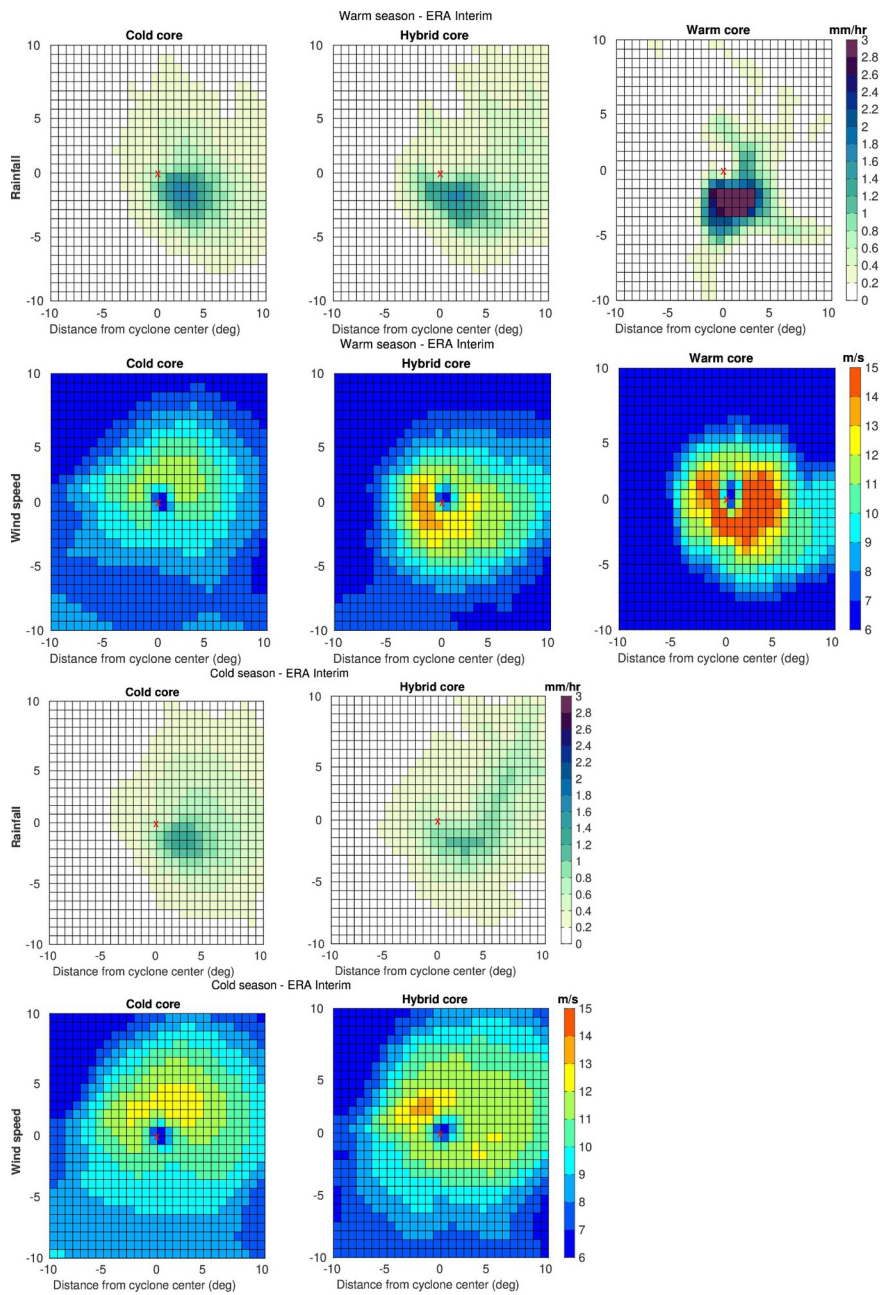


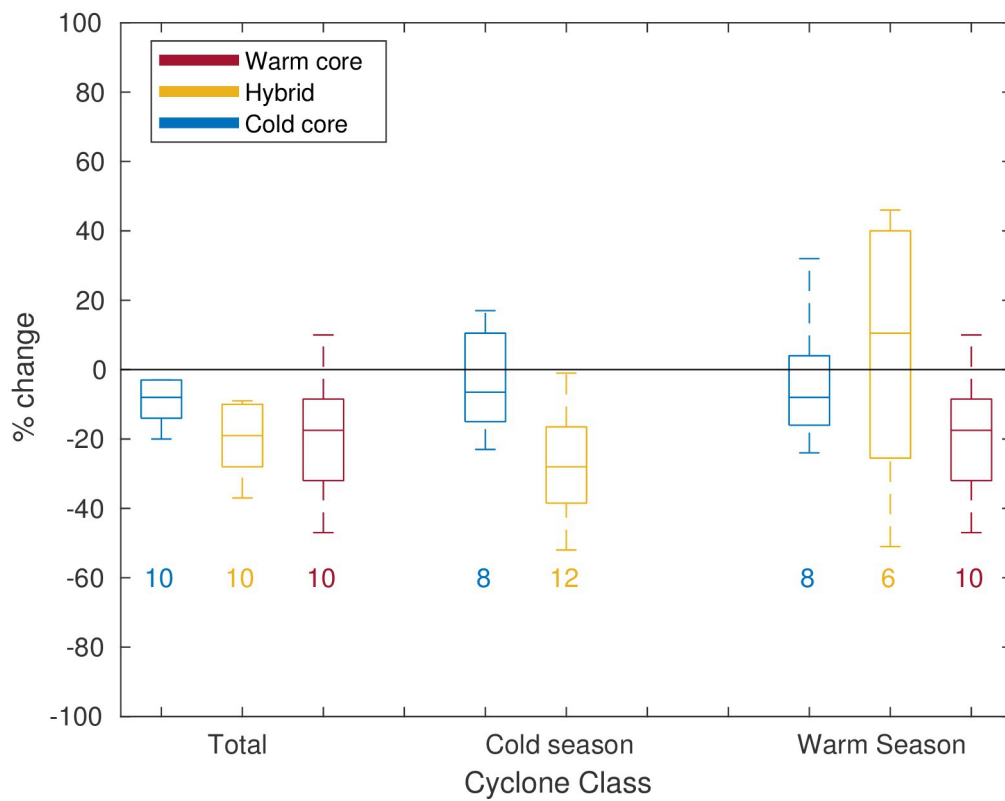
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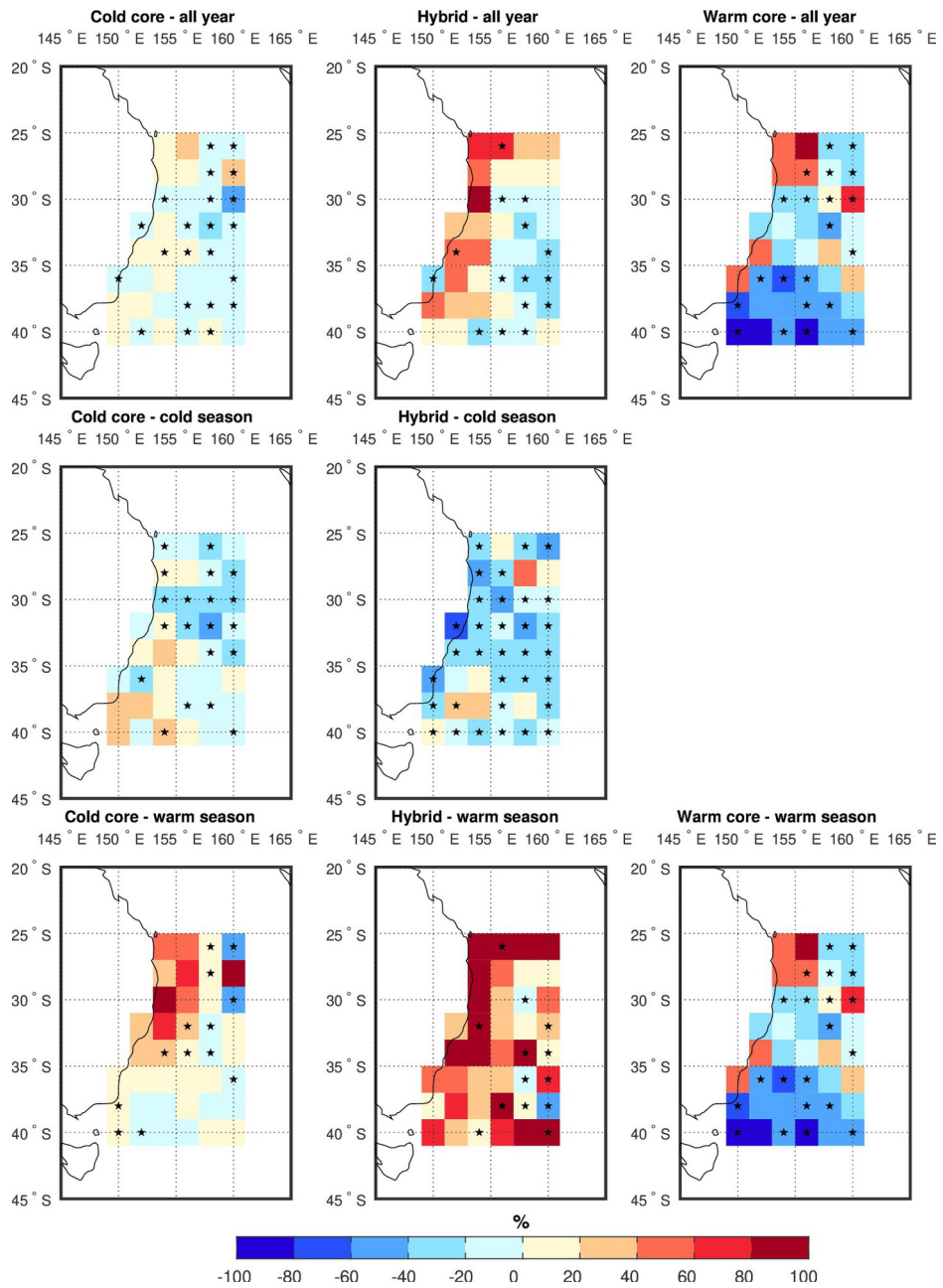




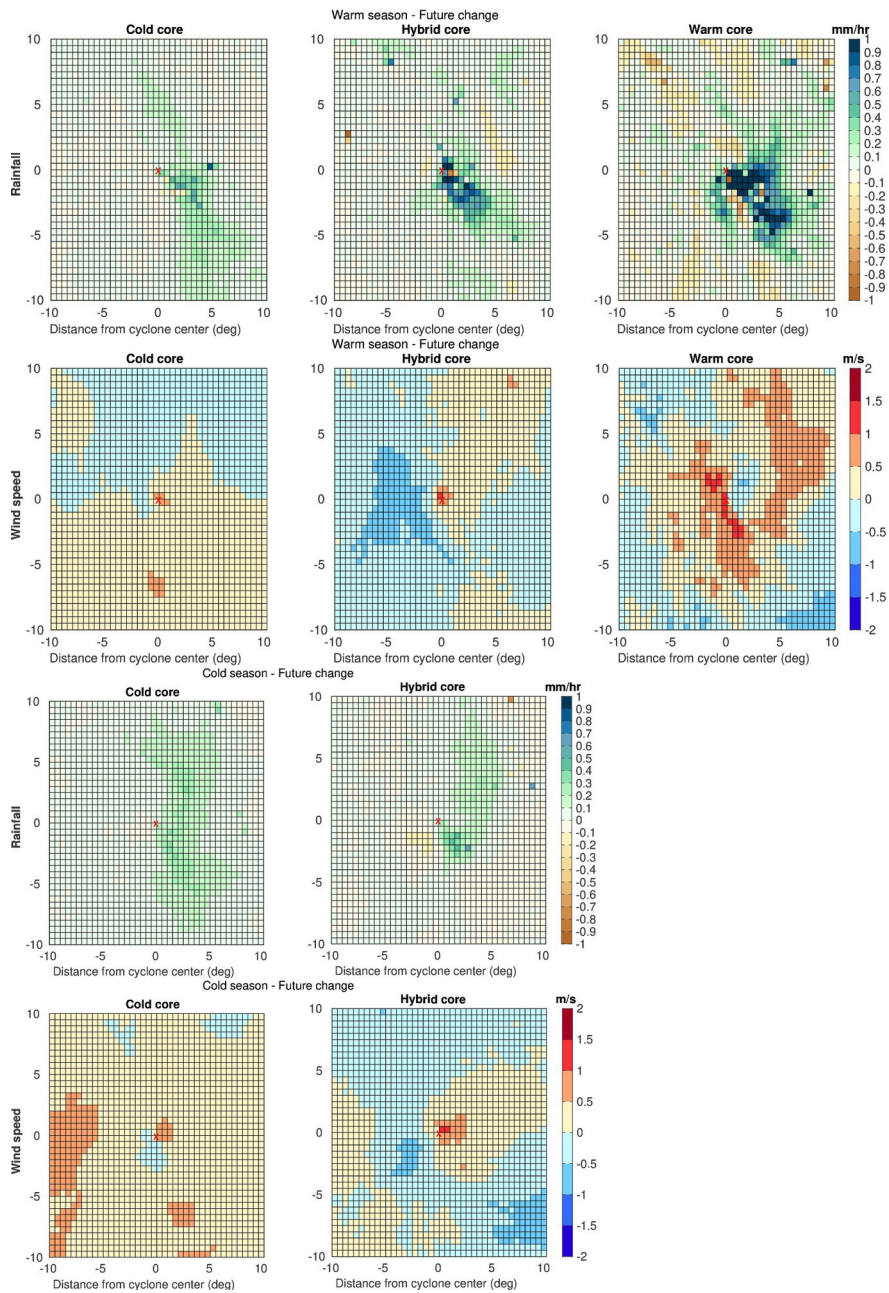
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