Response to Reviewers on 10.5194/cpd-11-181-2015 (Koh & Brierley)

Overall summary

Dear Dr Lohmann,

Thank you for the opportunity to submit a revised version of our manuscript. All three reviewers were in agreement that the original manuscript contained some value, but that its presentation was unintentionally misleading. They also suggested more detail be placed in the methods section to facilitate replication of the results. There were several more specific comments as well and I respond to those individually below.

I would also like to apologise for the delay in returning the manuscript. I found some errors in the model grid interpolation that required recomputing several GPI fields (all MIROC and the Hadley Pliocene models). The renormalisation and ensemble meaning process have been revised. I have also altered the colour scales to assist with colour blindness.

Yours,
Chris Brierley

Rob Korty

Koh and Brierley present an analysis of large-scale environmental conditions in simulations of the LGM, mid-Holocene, and Pliocene prepared for PMIP3 and PlioMIP. They find that most of the features reported by Korty et al. (2012), who performed a similar analysis on the older PMIP2 for the LGM and mid-Holocene, are present in the newer, higher-resolution versions in PMIP3. I'm delighted to see the results they have presented, and believe there is great value in the work they've done.

We are pleased that Dr Korty feels there is a great value in the sort of analysis that we have performed. At times, I was worried that it was a little too descriptive.

But one issue that affects the entire paper is a misapplication of the term "genesis" when what this paper actually presents is an analysis of variables that are known to be important for genesis (wind shear, vorticity, various thermodynamic quantities). This is a critical problem in need of urgent repair. Even the title of the paper is affected! The work here does not examine genesis across paleoclimates; rather, it examines how the conditions necessary for genesis to occur change across paleoclimate simulations. (It would be proper to call these genesis factors, or large-scale environmental conditions, or something of that sort.)

All reviewers have raised this issue and I can see their point. In our discussions when deriving the results we always used the term 'genesis' as shorthand – both of us had full knowledge of the inherent caveats in that term. It was however inappropriate to let such language permeate through the submitted manuscript. I have rewritten the manuscript to remove such sloppiness.

Relatedly, one critical detail was not clearly presented in the manuscript: were these analyses done with monthly averaged data? With daily data? With climatologically averaged data (i.e., where data from each "January" is averaged with all other "Januaries" to form an averaged annual cycle)? As the comment posted by Matt Huber earlier this week notes, these are nonlinear quantities, and they will differ depending on the order of averaging. (We found in Korty et al. that the qualitative results were not sensitive, however, to these differences.)

I have added a sentence in the methods section stating that climatological averages were used. We had also tested the order of averaging and found that it made little difference to the qualitative results, but required substantially more effort, both computationally and logistically (Jean-Yves has kindly computed the averages on ESGF; and the PlioMIP database consists solely of climatological averages, so individual researchers would have needed to be contacted).

What does matter about the temporal frequency is what types of analyses are possible with the data. I suspect that these were likely from monthly mean climatologies or monthly averaged data (the phrasing in part of Section 2 seems to suggest this), in which case there are no tropical cyclones actually present or tracked in any of the data. So the language that permeates the paper about "cyclone frequency" or "cyclone genesis" is extraordinarily misleading. It gives the false impression that individual model storms have been defined, tracked, and aggregated and presented. In fact, that would only be possible if the frequency were 6 hourly or finer, and a particular tracking algorithm (e.g., Camargo and Zebiak 2002, among many others) were defined and employed. If I am correct that what is presented here is solely genesis factors and the genesis potential index, care must be given to presenting what such an index actually is. It is not measuring any actual genesis, only identifying where the combination of large-scale factors conducive for it are present. It is an empirical formula that in effect regressed large-scale environmental conditions against a dataset of contemporary record of actual storms. With no evidence of how many storms occurred during the LGM or Pliocene, there is no way to calibrate such an index for a prior climate. In this case, the index is merely one tool for summarizing how the environment changes.

We have altered the presentation of these results to rectify the terminology issue. The applicability of the GPI to past climates is an assumption that we had not made explicit. It is now included at the beginning of section 3, with a reference to Suzana Camargo's recent paper. We have added a paragraph at the end of the section 3 emphasizing what the metric can and cannot say about tropical cyclones.

(And it is just one possible way to summarize it, which is why I advocate for the individual factors ought to be presented and discussed, as they are here.)

In both of Dr Korty's papers on PMIP2, the individual factors are presented in much more detail then we perform here. We only mention the factors briefly in the discussion section. We had felt that the manuscript is already lengthy and it was not worth including additional figures. In places I have increased the discussion to provide more information about the mechanisms (although more in response to Tim Merlis' comments).

The problem with the paper as it stands is the use of terminology—beginning with the title and line 1 of the abstract—about changes in cyclone "genesis". What this paper is actually presenting are changes to large-scale environmental conditions that are known to be important to genesis. This is a critical distinction that needs to be corrected. I have tried to catalog examples of this below, though the list is by no means exhaustive; a careful editing of the entire manuscript to purge these phrases is necessary.

Specific comments: The principal problem begins with the title, and then on line 1 of the abstract: this paper does not investigate tropical cyclone genesis, but rather conditions that are necessary for genesis. Abstract lines 9-10: Given the data used in this study, one cannot assess cyclone frequency or spatial patterns of cyclogenesis; you can only assess changes to the conditions that are necessary for it. Abstract, lines 13-20: Same as before; you are not assessing changes in genesis, but rather how the large-scale conditions that allow it differ.

The title and abstract have been revised to reflect the analysis more appropriately.

Line 2, page 185: you are not assessing TC activity in these simulations unless you track specific features or simulate them using various downscaling methods. What is presented here are analyses of how environmental conditions differ.

This is valid point, We have written a new paragraph discussing the limitations of the work in Section 3.

Section 2: This section needs to detail what data is analyzed. What is the frequency of the output (monthly, etc.)? What is the vertical resolution, how high into the stratosphere are temperature data available (this affects potential intensity)?

I had felt that this section already provided sufficient details – although in light of the reviewers' comments this clearly was not the case.

We now explicitly state that all the data is climatological averages (previously we had only stated how we created a climatology). Discussion of the vertical resolution is now also included in Section 2.

Line 4, page 187: although we modified Emanuel's earlier index by employing a "clipped vorticity" dependence, Tippett et al. (2011) should be referenced here; that is the paper that showed vorticity was not a rate limiting factor in these genesis indices.

This reference has been altered in Section 3. We have also corrected the year of the Tippett work throughout the revised manuscript.

Line 10, page 187: A tropical storm is defined when winds exceed 17 m/s, not 35. The 35 m/s in the index is unrelated to this definition.

Good point. The offending sentence has been removed.

Lines 12-16, page 187: If you wish to include the coefficient b in your definition of the genesis potential index, why not choose a value that normalizes GPI to yield a value of 80 or 90 per annum in the preindustrial era control of each model (a model-specific value of the coefficient)? What matters here are how the factors change away from their values in the control climate of their own particular model. By using a single number across the ensemble, you give the impression that one model produces many storms and another few, when in fact you're merely comparing how representations of the large-scale conditions vary. The raw numbers are very likely to differ with model resolution, which varies from model to model. This issue feeds into my larger concern that the way this was presented left an impression that you had tracked actual model-generated storms, when that is not the case.

We had adopted this approach following Dr Korty's previous work. Following the interactive discussion on this point, we have recomputed the figures with varying b. I have also added a footnote for the reader to compare this manuscript with the discussion paper to see the impact of this choice.

Line 5, page 191: No model is simulating genesis here; they are producing conditions that should support genesis.

This sentence has been replaced with "All models simulate conditions favourable for cyclone genesis…"

Line 8 page 191: Same problem with wording; conditions in the southern Indian Ocean may be more favorable in JFMA with limited potential in JASO.

This sentence now reads: "Stronger GPI in the southern Indian Ocean is found during JFMA, with limited genesis potential in the…"

Line 15 page 191: Again, there is no intensity of cyclone genesis; rather, there are large-scale conditions that are more favorable.

The beginning of the sentence now reads "CCSM4 and IPSL-CM5A-LR exhibit a band of GPI…". Note the whole sentence has been rewritten in light of the modified *b* giving a subtly different pattern.

Line 27 page 191: genesis potential, not intensity.

The sentence now reads "…highly similar distribution of genesis potential index for regions such as …" instead

Line 13 page 192: You do not diagnose cylcogenesis in any of the five models; you calculate a genesis potential index for each.

This has been replaced with "These insolation changes drive responses in simulated genesis potential index across the five models"

Lines 27-28, page 192: this indicates a shift in the region where conditions most favor genesis, not a shift in genesis itself.

This whole sentence has been removed in light of the revised results.

Lines 3-4, page 193: There is a decrease in the favorability of conditions in the Northern Hemisphere, not in genesis. Opposite in the Southern.

"cyclone genesis" has been replaced by GPI in both occurrences in this sentence.

Lines 5, 6, 7, page 193: Same problem with terminology.

This sentence has been revised with GPI replacing 'cyclone genesis' in the first instance and the second instance has been removed completely.

Line 9, page 193: In Korty et al., we did not diagnose genesis, but rather genesis potential. There are many other examples of this throughout the remainder of Sections 4, 5, and 6; rather than document all of them here, a careful editing to purge the manuscript of all language of genesis where genesis potential index was meant is necessary.

We appreciate this oversight. I believe that I've now caught all the offenders, but am happy to correct further instances where necessary.

Section 4.6: The presentation of this entire section should be rethought in light of my comments about what the index really is. This is not an analysis of frequency, but rather whether conditions are moving in a direction that are more or less favorable.

This section has been rewritten. I have chosen to adopt the term 'cumulative GPI' to describe the annual, global integral of the GPI field instead of 'storm frequency'. I hope that is sufficient clear.

Table 2: The column titled "storms per year" must be changed. There are zero "storms per year" in all of your data! This is again very misleading as it creates the impression that you have tracked some number of storms in each model—perhaps 94 such events in CCSM4, for example. You are not tracking individual events; rather you are calculating an index of how favorable the large-scale atmosphere is. Whether or not CCSM4 generates 94, ten thousand, or zero storms in any year of simulation could only be determined by employing a definition of what a storm is in a GCM and then applying an algorithm to detect how often that definition is met. That would require at least 4 times daily data, which is not available for most fields in most paleoclimate models.

What I recommend here is that you choose a value of the coefficient b that would normalize each model's preindustrial era to either 80 or 90 per annum .That would mean a smaller coefficient than you used for CCSM4 and MIROC4m, for example, while a larger one for FGOALS, HADGEM2, IPSL, and MIROC-ESM. You should then replace the "storms per year" column in this table with the value of b used in the formula for that model.

This has been altered after the interactive discussion. We have adopted varying values of *b* to give 90 'storms' per year in the preindustrial control simulation of each model. Table 2 now includes *b* instead of 'storms per year'.

Prof. Huber

This is a review of Koh and Brierley, "Tropical cyclone genesis across palaeoclimates". The issue of how tropical cyclones (TCs) have changed in the past and future is an important scientific problem, with important implications. To my mind, the most interesting part of this problem is the potential role tropical cyclones play as feedbacks in the climate system, but that is not something really addressable in this paper as currently framed. So while this vitiates some of the potential interest and importance of the results, the paper still has merits as a step in the direction of using complex models to answer first order questions about how TC activity may have changed in the past.

I (CB) cannot help but agree with Prof. Huber that the possibility of cyclone-climate feedbacks is the most interesting aspect of palaeohurricanes. However, the necessary code modifications to really investigate the feedbacks mean that they are really tricky to look at across multiple models. Here we set out on a data-mining exercise of the PMIP3 database, which severely constrains the range of possible analysis.

I think I am not the only one who will find the presentation somewhat confusing, but this is easily remedied by altering the title and some of the verbiage in the paper.

We have now revised the title, text and presentation to make things a bit clearer.

Since Climate of the Past may not have an audience that is very knowledgeable about TC activity and the theory and metrics which surround it, I think that some more plain language about what is and what is not being studied and constrained is in order. For example, the results do not provide information on how many storms will reach maturity, how long they will last, how strong they will be, or where they will go. Those are some pretty large limitations and they should be put right up front near the beginning of the paper in a language that the broad readership of CoP can understand. I would clear things up in the beginning better, as well as a more detailed explanation of the methods for readers who may want to duplicate and extend the results. I think that adding a more clear section about the limitations and assumptions is important. I have raised three of those in the short comments and I find the brief responses to be a good basis for a more formal *response and I encourage the authors to include a section describing some of these limitations better.*

The new (long) summary paragraph in section 3 is dedicated on spelling out these limitations. Hopefully the revisions in the introduction and abstract should also make this a bit clearer. The methods have been described at more length to assist with subsequent analysis.

I am also particularly concerned about highlighting for readers that the use of 'correct' SSTs might substantially alter the results. The approach that the authors have taken is fine with me, but it will be good that people can understand how these results might be an example of garbage in=garbage out. I do not believe in a literal interpretation of proxy data and that is not what I am arguing for here, but merely to acknowledge that the models have large and well quantified biases for these time intervals and it is eminently plausible that with different SSTs the result might be different.

That is a very good point and one that we hadn't really raised at all in the original manuscript. The new section 5.1 is devoted solely to this issue.

Dr Tim Merlis

The manuscript presents an analysis of changs in a tropical cyclone genesis potential index (GPI) for several GCMs in four perturbation climate states—spanning past and future climate. As the authors note, genesis indices have been examined for future climate in a number of studies, but only the recent publications by Rob Korty et al. have examined them for past climates. The manuscript adds to the existing literature by considering simulations of the Pliocence climate and repeating the Korty-led analysis of the climate of the Last Glaicial Maximum and mid-Holocene in the newer paleoclimate model intercomparision phase 3 (PMIP3) simulations. Given this contribution, the manuscript should be published following some revisions that largely pertain to the presentation of the results. [I note that I have not read the other comments before preparing my review.]

Major suggestions/concerns:
1) A key concern I have regarding the presentation of the results of the analysis is that the changes in the GCMs' GPI is often discussed as a "response in TC genesis" (e.g., p. 184 L25). It is very important to use clear terminology, as there is research about TC-climate changes that assesses the environmental factors known to affect genesis in today's climate (as encapsulated by genesis indices or GPIs, which is what the authors do) and there is research that uses high-resolution GCM simulations that explicitly simulate TCs (various GCM groups over the last decade, several of which are referenced in the manuscript) with the downscaling approach used by Emanuel falling in the category of explicitly simulating TCs. This is a concern for both clarity for readers and accuracy—the ~300 km coupled GCM simulations analyzed in the manuscript cannot tell us how "TC genesis changes" but can tell us how "environmental factors that affect TC genesis change" or "how

GPI changes". This issue comes up in the main text, Table 2, and most importantly the title of the manuscript. I suggest the title is changed to something along the lines of "Tropical cyclone genesis indices across palaeoclimates".

The wording throughout the manuscript has been altered to remove this pervasive issue. We have also altered the title and abstract.

2) I think it is important to note that GPIs have difficulty when climate changes are separated into direct responses to forcing (e.g., change in CO2 concentration) and temperature-dependent responses. Held & Zhao 2011 (and a couple of early references that you can find therein) show there are direct TC frequency changes from forcing in TC-permitting GCM simulations and Camargo and co-authors have tried various GPIs on this case ("Testing... HiRAM..." J. Climate).

I appreciate this issue, but feel it is rather minor in the current study, which primarily looks at 'equilibrium' climate states. In this instance, distinguishing between the forcing and the temperature responses seems a relatively mute point. This is clearly not true for the transient simulations though and we now mention this as a possible cause of the discrepancy between the past and future runs (section 5.2). We had also neglected to highlight the caveats on applying the GPI to alternates climates (stemming ultimately from this issue), which is now discussed explicitly in section 3 (including a reference to Camargo and co-authors).

3) Using the same 'b', the coefficient that allows the index to match the observed amount of genesis, for all the simulations is problematic when the ensemble mean is the focus. Table 2 shows that this results in factor of 3 intermodel variations in the GPI's global number per year. An example: if you have one GCM with 90/yr (like CCSM) and one with 30/yr (like IPSL) and they have opposing 10% changes, the ensemble mean would have a ~5% change. Whereas, if 'b' was adjusted so that all models had the same preindustrial N/yr, opposing 10% changes would lead to no change in the ensemble mean.

We have altered our approach to the ensemble averaging. 'b' now acts to normalise the impacts across the ensemble. We have chosen not to present the GPI as a % change, as it becomes visually dominated by minuscule absolute changes in regions very unfavourable to TC genesis.

4) The manuscript does not have too much discussion or figures of how individual factors in GPI change across the climate states. This is one of the appealing aspects of using GPIs—they can be broken down to say which environmental factor dominates the change in the index. It might be nice to include more summary of this, but I understand that it would be difficult to systematically present all of the factors for all of the climate states.

We have increased a little the mentions of the constituent environmental factors in the manuscript. The manuscript already covers a lot of ground and adding any new figures would make it unwieldy in our opinion. We actually support the explanations given by Rob Korty's manuscripts on causes in most cases, so have focussed the discussion in reference to those.

5) In 4.6, I think it would be nice to also express the change in global GPI in % per K of tropical SST change. It doesn't look like one number will work across climate states and this is an interesting result.

It is an interesting result. We had tried to bring this out more in the discussion. In fact, even with marginally more advanced metrics no obvious correlation is found (e.g. NH GPI and NH Tropical SST).

Minor suggestions/concerns:
** Stating the parameters used for the potential intensity calculation is good to ensure reproducibility. Also, It's conceivable that this accounts for some of the divergence between the manuscript's assessment of the RCP scenario and the other publications that have assessed those same simulations.*

We have increased the description of the methodology relating to this.

** There is some discussion of the role of the ITCZ on TC genesis (abstract and section 5). I suggest the authors check out my 2013 GRL paper co-authored by M. Zhao and I. M. Held and a JAS paper that is in press led by Andrew Ballinger (with 3 other authors from the GRL) for research that is directly examining this connection.*

Thank you for making me aware of these two papers. They are now included in the discussion of the ITCZ movement.

** Introduction the GPI used in this paper. I think the lineage of the index used in Korty et al. is a combination of Tippett et al. 2010 and Emanuel et al. 2010, which in turn modified the Emanuel and Nolan 2004 index. Emanuel et al. 2010 increased the exponents on the vorticity and shear over EN04.*

Thank you for that clarification. Dr Korty confirmed this lineage as well. We have now revised the references.

** In 4.6, the text has a different number of the Pliocene compared to figures 9 and 10.*

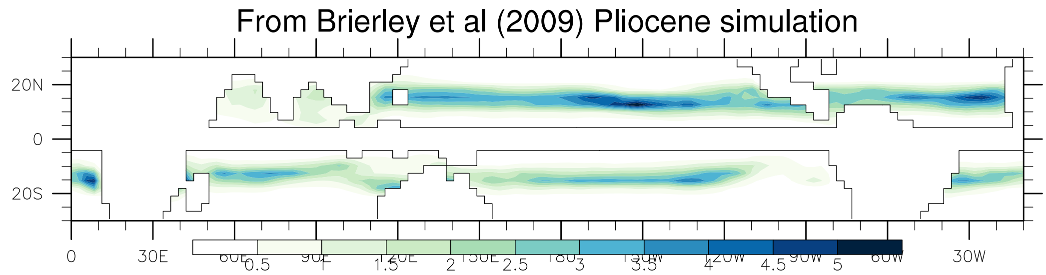
I really appreciate this observation. On the surface, this was caused a failure to update the summary spreadsheet after reprocessing a simulation. However, in digging into the code to output the summary numbers more effectively, I came across an error relating to the interpolation of the SST onto the model grid for both the MIROC and Pliocene HadCM3 simulations. I have now fixed this error, and therefore all these values have changed.

** In section 5, Bengtsson et al. 2006 and Held and Zhao 2011 have also connected strength of convection to TC genesis. I have a personal interest in knowing if the ascent over the ocean weakens in the mid-Holocene simulations, as I found this in* *idealized simulations of orbital precession (Merlis et al. 2013 Part I, J Climate). I understand this is not central to the manuscript.*

I am afraid that we did not collect vertical velocities from the PMIP3 database for this analysis. I would be happy to talk individually about this being a subsequent area for study with the reviewer though.

** It would be interesting to know what the GPI is for the fixed SST Pliocence simulation used in Fedorov et al. 2010.*

That's a good question. In response to this and Prof. Huber's comments, we have created a new section specifically to compare and contrast the conclusions of the two studies. As to the actual GPI from the simulations, I must confess that I have messed up my data archiving. I have the relevant tar.gz files from the simulations, but can't actually extract any meaningful data from them. I've had a hunt around and the best I can do is from a simulation in my earlier manuscript (Brierley et al., 2009, Science). I don't even have the required data from the control run – so all I can show you is the pattern of genesis not the numbers themselves. I can't calculate b to normalise it (because of the lack of control run) and have used b=2.2x10^4 here to get the range from between 1 and 5 x10^{-13} in the picture below. This b is an order of magnitude higher than used for the coupled runs. I therefore suspect that there is a reduced maximum genesis, but can't say for certain. Sorry again about my poor data archiving.



** Angular precession in Table 1 should specify that the angle is relative to the NH autumnal equinox.*

This has been amended in the revised document.

** For the variability of the genesis index: I think this is a lower bound on the variability of TC genesis. Villarini and Vecchi have a series of papers using statistical estimates of TC activity based on environmental factors, so you could see what their interpretation is of this.*

Thank you for bringing this work to our attention. We now include a few sentences on our estimate of internal variability of the index in section 3 and cite these references.

Tropical cyclone genesis potential across palaeoclimates.

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Abstract

The favourability of the Pliocene, Last Glacial Maximum (LGM) and the mid-Holocene for tropical cyclone formation is investigated. through analysis of, A genesis potential index, derived from large-scale atmospheric properties known to be related to storm formation, is calculated for five climate models. The mid-Pliocene and LGM characterise periods where carbon dioxide levels were higher and lower than preindustrial respectively, while the mid-Holocene differed primarily in its orbital configuration. The cumulative global genesis potential is found to be fairly invariant across the palaeoclimates in the multi-model mean. Despite this all ensemble members agree on coherent responses in the spatial patterns of genesis potential change.

During the Pliocene and LGM, changes in carbon dioxide led to sea surface temperature changes throughout the tropics, yet the potential intensity (a measure associated with maximum tropical cyclone strength) is simulated to be relatively insensitive to these changes. Changes in tropical cyclone genesis potential during the mid-Holocene are found to be asymmetric about the Equator: being reduced in the northern hemisphere, but enhanced in the southern hemisphere. This is clearly driven by the altered seasonal insolation. Nonetheless, the enhanced seasonality drove localised changes in genesis potential, by altering the strength of monsoons and shifting of the Inter-tropical Convergence Zone. Trends in future tropical cyclone genesis potential are neither consistent between the five models studied, nor with the palaeoclimate results. It is not clear why this should be the case.

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1 Introduction

Tropical cyclones (TC) constitute one of the most powerful forces of nature and can cause severe destruction to human life and property. How TC genesis may change in the face of climate change is thus an area of strong interest. Past studies using high resolution general circulation models (GCMs) have generally suggested that cyclone intensity would strengthen, yet cyclone genesis would decline in a warming climate (Knutson et al. 2010). However, recent analyses of future simulations performed as part of the Coupled Model Intercomparison Project Phase 5 (CMIP5) appear equivocal: statistical downscaling indicates an increase in both cyclone intensity and genesis (Emanuel 2013); dynamical downscaling indicates an increase in intensity combined with a reduction in frequency (Knutson et al., 2013); tracking algorithms of global coupled models do likewise (Camargo, 2013); large-scale cyclogenesis indices have shown both frequency increases (Emanuel, 2013) and decreases (Camargo, 2013).

Understanding past climates provides a means for scientists to contextualise future climate change impacts. Palaeoclimates with altered climate forcings, such as the elevated levels of carbon dioxide during the Pliocene period, may provide clues on how the trend of cyclone genesis would respond to ongoing anthropogenic emissions of greenhouse gases.

The mid-Piacenzian warm portion of the mid-Pliocene (around 3 million years ago, henceforth "Pliocene") was a recent episode in Earth's geological history where mean global temperatures were warmer by 2-3°C compared to modern times (Haywood et al. 2013), but the warming was not constant across the globe. Sea surface temperature (SST) anomalies were more pronounced at the higher latitudes (up to 20°C in the high Arctic; Ballantyne et al. 2009), while the lower latitudes exhibited minimal change in places (Dowsett et al., 2010). The geography of the continents and oceans were relatively similar to earth's current configuration (Haywood et al. 2011). Carbon dioxide levels were at near present day during the mid-Pliocene (Pagani et al. 2009). There is potential of using the Pliocene to learn about the equilibrium state of earth's warm climate following anthropogenic greenhouse gas influence (Haywood et al. 2009).

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Meanwhile, the icehouse climate of the Last Glacial Maximum (LGM) at 21ka serves as a contrast to our current greenhouse climate. Proxy estimates by Annan and Hargreaves (2013) suggest that LGM tropical SST was around 1.6°C lower than preindustrial, while global surface air temperatures were 3.1-4.7°C cooler. Given the relatively similar orbital parameters controlling earth's solar insolation during the Pliocene, LGM and preindustrial periods, the focus of the Palaeoclimate Model Intercomparison Project (PMIP) on these eras help facilitate studies that examine the effect of carbon dioxide concentration changes on the tropical climate (Table 1).

On the other hand, simulations for the mid-Holocene epoch at 6ka differ from preindustrial conditions mainly in the orbital parameters that result in an increased insolation in the high latitudes. The tropical region of the mid-Holocene period might have encountered slightly elevated sea-surface temperatures (SST) of around 1 °C (Gagan et al. 1998), although recent studies indicate some uncertainty in terms of negative SST anomaly for regions such as the western Indian Ocean (Kuhnert et al. 2014). Despite the limited proxy record agreement on whether tropical oceans may have warmed (Koutavas et al. 2002; Rimbu et al. 2004; Stott et al. 2004), prior PMIP simulations suggest SST in the northern hemisphere was generally warmer by less than 1 °C in the mid-Holocene period compared to the preindustrial era, and the southern hemisphere might have been slightly cooler (Braconnot et al. 2007).

Given the lack of data on tropical cyclone frequency for the palaeoclimates, model simulation studies cannot seek to verify model response on cyclone formation, but rather aim to describe tropical cyclone trends with the assumption that signals would be detectable by using indicators such as cyclogenesis potential. Using PMIP Phase 2 (PMIP2) data, studies have been conducted to investigate indices related to TC genesis activity during the LGM and mid-Holocene periods (Korty et al., 2012a,b). These have been unable to analyse simulated tropical cyclones directly, due to the unavailability of six-hourly data throughout the atmosphere in the data archive. Instead those studies (and the present one) look at indices describing how favourable the climate state is for tropical cyclogenesis. For the LGM, Korty et al. (2012a) observed higher genesis potential relative to the preindustrial era. For the mid-Holocene era, Korty et al. (2012b) demonstrated that the difference in distribution of the top-of-atmosphere (TOA) radiation in comparison to the preindustrial control altered the seasonal

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cycle of potential intensity (maximum achievable storm strength) in the Northern Hemisphere. There was mixed response in TC genesis potential for the mid-Holocene relative to the preindustrial period, the northern hemisphere becomes slightly less favourable for TC activity, whilst the southern hemisphere becomes more favourable.

This study aims to investigate if similar behaviours are seen in the subsequent generation of PMIP; namely the PMIP3 model ensemble. The related Pliocene ensemble (PlioMIP) is included to investigate whether there is a robust response to carbon dioxide concentrations. A further objective is to explore how factors associated with TC genesis in these palaeoclimates (equilibrium states) relates to those under future simulations (transient scenarios).

The various model simulations used in this study are described in Section 2. The calculation of genesis potential index (GPI) that underpins this study will be presented in Section 3 of this paper along with its limitations. Section 4 consolidates the results from the GPI analysis of the various palaeoclimates derived from the GCM ensembles. Unfortunately measures of storm frequency, intensity and landfall are not possible with this methodology and so cannot be analysed. A discussion of how the climatology in the Pliocene, LGM and mid-Holocene may affect TC genesis potential relative to the preindustrial period will be covered in section 5, as will the effects of elevated carbon dioxide concentration on GPI. Section 6 will summarise this paper's key findings.

2 Climate Simulations

The Pliocene Model Intercomparison Project (PlioMIP), which complements the LGM and the mid-Holocene aspects of the PMIP Phase 3 (PMIP 3), coordinates the efforts of various international climate modelling teams to quantify uncertainties in model outputs using the average interglacial conditions of the mid-Piacenzian (hereafter known as Pliocene) climate boundary conditions between 3.29 Ma and 2.97 Ma (Haywood et al. 2011).

Nine coupled climate models participated in PlioMIP (Haywood et al. 2013), although only five are analysed here. The GCM dataset selection for this study is largely dependent on data

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availability for the large-scale climatic variables, such as the atmospheric temperature and humidity profile, from the PlioMIP project for the Pliocene epoch. PMIP3 data for the LGM, mid-Holocene and preindustrial are taken from the same GCM that is used in the Pliocene simulation. In one instance a different GCM from the same model family (MIROC) was used in the PlioMIP compared to the rest of PMIP. Here a preindustrial control from that particular GCM generation was used for comparison. A similar approach is taken for HadCM3, where intriguingly the PlioMIP and PMIP preindustrial simulations show different properties (perhaps an undocumented model improvement has been included in the PlioMIP version). Data for the representative concentration pathway 8.5 W/m^2 (RCP 8.5) is likewise analysed as an example of a future elevated carbon dioxide concentration scenario. The GCMs that have been included for this study are outlined in Table 2.

Throughout this work, the genesis potential index presented has been calculated using monthly climatological values of the climate model variables (rather than computing a climatology of monthly varying GPI). This approach was adopted for pragmatic reasons, although Korty et al. (2012a) suggest the impacts on the results are small. We investigated the sensitivity of this choice for a single GCM and also found it to be minor. In situations where a pre-computed monthly climatology of a particular epoch is not available on the Earth System Federation Grid, a 50-year time-slice from the end of the period of interest is used to generate the monthly climatology data so as to minimise stochastic effects, model drift and internal variability. The number of vertical levels used by each model are given in Table 2. However, as the models have a hybrid vertical coordinate, the actual number of pressure levels used for the PI computation often differs. Nonetheless, all models have data from well up into the stratosphere. The GPI is only calculated between 30°S and 30°N and the cumulative values given in this study represent the integral over this latitude band. The ensemble mean is obtained by first bi-linearly interpolating the individual model fields onto the coarsest-resolution grid (HadCM3 in this case) and then averaging. Any missing data (i.e. land) is infilled prior to the regridding and then the coarsest-resolution land-sea mask reapplied subsequently.

Calculating the range associated with internal variability in GPI is challenging. Here ten 10-year time-slices are taken from a hundred year dataset of the preindustrial dataset of each

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model. The standard deviation (SD) is found to be within 1-3% of the preindustrial (PI) TC genesis annual frequencies simulated across the five GCMs (Table 2). It is not clear to us how the longer-term internal variability (i.e. that associated with climatologies) relates to this estimate. Intuitively one may expect it to be smaller, as the climatology averages over more ENSO cycles than the decadal estimates. However, research into the interannual applicability of large-scale storm-related metrics (such as GPI) suggest that they underestimate the variability (Villarini and Vecchi, 2012).

3 Genesis Potential Index

The use of "genesis potential" is particularly useful for cyclone-related with climate models. The grid resolution of most GCMs is not sufficiently refined to simulate mesoscale processes required to adequately capture tropical cyclones. Many studies have used genesis potential indices as a less computationally intensive and more practical approach to describe how favourable climate conditions for the tropical cyclogenesis (Bruyère et al. 2012; Camargo et al. 2007; Emanuel and Nolan 2004; Korty et al. 2012a, b; Menkes et al. 2012; Tippett et al. 2011).

Gray (1975) pioneered work on an genesis potential index (GPI) by demonstrating the use of selected diagnostics such as mid-troposphere humidity, vertical shear of the horizontal winds between the high and low level troposphere, low level relative vorticity, and thermal parameters related to SST to characterise climatic conditions that are favourable for cyclone genesis. The subsequent GPI improved by Emanuel and Nolan (2004) is considered state-of-the-art (Tippett et al. 2011) and incorporates the potential intensity theory (Emanuel 1988; Holland 1997) that evaluates the maximum wind speed that may be attainable using the available thermodynamic energy imparted from the atmospheric environment and the sea surface (Camargo et al. 2013) to the TC. It is worth noting that just because a genesis potential index that performs well in the modern climate, it may not adequately capture the actual response of cyclogenesis to a changed climate (Camargo et al., 2014). In the following description, we must assume that the GPI index described below - derived from modern observations - represents changes in cyclogenesis in past climate simulations as well.

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The GPI proposed by Emanuel and Nolan (2004) serves to synergise the thermodynamic and kinematic factors affecting TC genesis into a single index. With the aim of facilitating comparison with previous investigations into palaeoclimate cyclone genesis, the "clipped vorticity" version of the GPI employed by Korty et al (2012a, b) has likewise been adopted for this study:

$$GPI = \frac{b[\min(|\eta|, 4\times10^{-5})]^3[\max(PI - 35{,}0)]^2}{\mathcal{X}_m^{\frac{4}{3}}[25 + V_{shear}]^4} \quad (1)$$

Here, η represents the absolute vorticity computed at the 850hPa level (Nolan and Rappin 2008), V_{shear} is the 200-850 hPa wind shear value, $\mathcal{X}_m$ is the moist entropy deficit. PI is the maximum potential intensity a TC can theoretically achieve (Emanuel 1988). Due to the inherent biases in convection schemes and parameterisations employed by GCMs, the global annual total TC genesis has to be calibrated (Emanuel et al. 2008b). b is therefore an empirically derived normalisation factor that calibrates the GPI to achieve preindustrial cumulative annual cyclone genesis frequencies of the ninety storms observed per year in the modern period. This approach means that the percentage changes in local GPI for each model will be reflected in the ensemble mean. Previous work (Korty et al., 2012a,b) used a constant value of b across the ensemble. Such an approach would mean that small absolute changes in GPI in modelled conditions biased against cyclone genesis contribute less to the ensemble mean picture. It is not clear which approach is the most relevant in this context.[1]

Wind shear and absolute vorticity are the two kinematic factors included in the GPI, while potential intensity and moist entropy deficit are both thermodynamic factors (Korty et al. 2012a). Wind shear, which is the vertical shear of the horizontal winds between the upper and lower troposphere, causes asymmetries in the developing cyclone which results in the ventilation of the upper level warm core through the flushing of relatively cooler and drier air from the top (Frank and Ritchie 2001). Stronger wind shear therefore influences inflow

[1] In the initial submission of this manuscript the constant b approach of Korty et al. (2012a,b) was used. We therefore invite the reader to compare the present figures to those visible from the open review stage to observe the impact of this choice on the ensemble mean patterns.

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dynamics and weakens cyclone formation (Riemer et al. 2013). While noting caveats where such two-level vector differentials may be inadequate to describe the resultant wind shear in some scenarios (Velden and Sears 2014), this study defines the wind shear as the difference between the 200hPa and 850hPa winds given its ease of computation.

Meanwhile, the vorticity serves as a spin-up mechanism that initiates cyclone formation in a recirculating flow that is quasi-closed in the lower troposphere. Taking the analogy of a protective pouch, the quasi-closed streamlines surround the enhanced vorticity while nurturing the thermodynamic and convective processes that favour TC development (Tory et al. 2012). Tippett et al. (2011) observed that vorticity has a greater influence on cyclone formation at lower latitudes, and other factors play a greater role at higher latitudes. They also propose incorporating a "clipped vorticity" diagnosis in place of absolute vorticity in the GPI, so as to moderate its response in over-estimating TC genesis for the sub-tropics. Potentially, the clipping threshold (set at 4×10^{-5} s^{-1} in eq. 1) may have varied in the past through large-scale changes in the atmosphere circulation. Sensitivity analysis performed indicates that changes in the clipping threshold appear to have little substantive impact on the resulting change in GPI for this study (not shown).

The non-dimensional term ($\mathcal{X}_m$) measures the moist entropy difference between the mid-troposphere and the boundary layer that is derived from asymmetric cyclone models (Emanuel 1995b), as shown below:

$$\mathcal{X}_m = \frac{s_b - s_m}{s_o^* - s_b} \equiv \frac{s^* - s_m}{s_o^* - s_b} \quad (2)$$

s_m, s_b and s_o^* represent the moist entropies of the mid-troposphere layer, boundary layer, and the sea surface saturation entropy respectively. Taking the assumption that the lapse rate of the tropical atmosphere is largely moist adiabatic (Emanuel et al. 2008b), s^* which is the saturation entropy above the boundary layer, is assumed to be constant throughout the atmospheric column. This allows the numerator term in Eq. (2) to be evaluated at 600hPa, which is taken to represent the mid-troposphere as defined by Emanuel (1994). s_b and s_o^* are

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calculated at 925 hPa for the boundary layer and at the sea surface respectively. We use the Bolton (1980) equation to calculate the saturation vapour pressures needed for the Emanuel (2008b) definition of moist entropy. Physically, a larger $\mathcal{X}_m$ signifies a longer duration needed for an initial perturbation to moisten the middle troposphere before intensification occurs (Emanuel et al. 2008b).

Taking on the analogy of a cyclone's evolution process as equivalent to Nature's Carnot engine (Emanuel 1988, 1991), the potential intensity diagnostic derived by Bister and Emanuel (1998, 2002) that takes into account the effects of dissipative heating is:

$$Potential\ Intensity\ (PI) = \sqrt{\frac{C_k}{C_d}\frac{SST}{T_o}(CAPE^* - CAPE_b)} \quad (1)$$

C_k and C_d are the surface exchange coefficients for enthalpy and momentum. Its ratio could range between 0.1 to 1.3 (Montgomery et al. 2010) and is likely between 0.75 and 1.5 for naturally occurring cyclones (Emanuel 1995a). In this study, a ratio of C_k/C_d=1 is taken to allow for ease of comparison with previous work that used a similar assumption (Korty et al. 2012a). T_o is an entropy-weighted mean temperature of the outflow. The convective available potential energy (CAPE*) describes an air parcel of maximum wind intensity that has been earlier saturated at the sea surface, while $CAPE_b$ describes a boundary layer air parcel which has been isothermally lowered from an equivalent air parcel of maximum wind intensity. Climate variables that are required for the potential intensity calculation include SST and pressure of the sea surface, as well as the humidity and temperature profile of the atmospheric column. The calculation of potential intensity for this study is facilitated by the use of a previously applied algorithm (Emanuel et al. 2008a).

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Having described both the genesis potential index and potential intensity, it is necessary to stress what these metrics can and, more importantly, cannot measure. Potential intensity assesses the environmental conditions and calculates the maximum strength a storm could achieve if it extracted all the available energy. It is not a measure the actual cyclone intensity,

which is often substantially smaller. The GPI is a measure of how favourable local atmospheric conditions are for tropical cyclone genesis to occur. A high GPI does not mean a storm will form at the location – other criteria such as an initial disturbance to act as storm seed are also needed. Changes in potential intensity and GPI combined provide useful information about how favourable past climates would have been for tropical cyclones to form and strengthen. However, they do not give us any information about many interesting aspects of tropical cyclones, such as their distribution, tracks, size, intensity or the ocean mixing they cause.

4 Results

4.1 Potential Intensity

In the tropical region, the Pliocene saw higher SSTs by about 2 °C relative to the preindustrial control (and the mid-Holocene), while SSTs were lower by about 2 °C at the LGM (Figure 1). Korty et al. (2012a) suggest that high values of potential intensity, typically higher than 55 ms^{-1}, are needed to induce deep tropospheric convection in TC genesis. Interestingly the locations of the 55 ms^{-1} potential intensity contour appears to be relatively insensitive to these wholesale SST changes. For example, the contour in the North Pacific is associated with SSTs ranging from 26 °C during the Pliocene to 22 °C at the LGM.

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During the Pliocene, there is a reduction in potential intensity for the North Atlantic despite an SST increase in the same region (Figure 1b). This supports research showing that absolute SST by itself can be an inadequate indicator of storm strength (Vecchi et al., 2008). Whilst, this may appear to depart from early understanding of threshold SST values (e.g. 26 °C) in influencing cyclone genesis (Palmen 1948), it rather underscores the importance of other factors, such as atmospheric humidity and upper troposphere outflow temperature relative to the SST, that jointly determine the magnitude of energy available to a tropical cyclone (Emanuel, 1998).

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4.2 Preindustrial

The preindustrial era serves as a useful reference climate as it is before Earth's environment came under substantial anthropogenic influence, especially over the tropical oceans (Lewis and Maslin, 2015). Figure 2 illustrates the Genesis Potential Index (GPI) seen in the various GCMs in their preindustrial simulations. After Korty et al (2015a,b), the northern hemisphere shows cyclone genesis potential averaged over the peak storm periods of July, August, September and October (JASO), while the southern hemisphere corresponds to the peak storm period of January, February, March, April (JFMA). Monthly storm genesis will be discussed in section 4.6.

The GPI distribution of the various GCMs compares favourably with the outcomes from similar model analysis by Camargo (2013) for the preindustrial period, despite the use of slightly different genesis potential indices. All models simulate conditions favourable for cyclone genesis from the eastern and western Pacific in the northern hemisphere during JASO, as well as the eastern Pacific near the South Pacific Convergence Zone (SPCZ) during JFMA. Stronger GPI in the southern Indian Ocean is found during JFMA, with limited genesis potential in the northern Indian Ocean during JASO apart from some areas such as the northern Bay of Bengal. The North Atlantic features some high genesis potential at the deep and sub-tropics, but the South Atlantic shows almost negligible potential for TC genesis. These features are all shown in observations of actual tropical cyclone genesis (Knapp et al., 2010).

However the various models do show some biases. CCSM4 and IPSL-CM5A-LR exhibit a band of GPI in the North Pacific that is too zonal. The East-West split in HadCM3, FGOALS-G2 and MIROC-ESM is more representative of Pacific observations. However both HadCM3 and MIROC-ESM have a West Pacific development region that is not sufficiently favourable for cyclogenesis and is constrained to the coastal regions. While IPSL-CM5A-LR suggests that the central-western Pacific would has its most favourable conditions for cyclone genesis, MIROC-ESM and HadCM3 show their greatest GPI in the north-eastern Pacific. FGOALS-G2 shows a relatively uniform strength of genesis potential across all the oceans, apart from an area of increased intensity in the eastern North Pacific and Philippine Sea. The genesis

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potential also stretches across a greater area in FGOALS-G2 relative to the other models. There appears insufficient GPI in the North Atlantic in nearly all the models, although CCSM4 and MIROC-ESM are especially weak. The Southern Hemisphere has a band of high GPI that is again a little too zonal in nature, although the southerly curvature in MIROC-ESM is commendable. This feature arises from the bias in the model representation of the SPCZ (Saint-Lu et al., 2015).

The ensemble mean (figure 2f) averages out the several of the biases seen by individual models. This PMIP3 preindustrial ensemble reveals highly similar distribution of genesis potential index for regions such as the North Atlantic, Pacific and Indian oceans in comparison with the 0ka genesis potential from Korty et al. (2012a) simulated using PMIP2 data from seven GCMs. In both instances, the highest intensity of genesis potential is located between the 10°-20° latitude belts of the respective peak storm periods of both hemispheres, and both are of comparable cumulative genesis magnitude of between 3-5 occurrences m^{-2} $month^{-1}$ (not shown). The preindustrial climate thus exhibits consistency in favourable cyclogenesis locations between the PMIP3 and PMIP2 simulations (only HadCM3 occurs in both ensembles).

4.3 Mid-Holocene

The key difference between the mid-Holocene and preindustrial climate lies in the changes in solar insolation arising from different angular precession (Table 1). As a result, the northern hemisphere receives proportionally greater insolation during its storm season compared to the southern hemisphere. The summer and annual mean insolation for the high latitudes in both hemispheres is also increased (Braconnot et al. 2007).

These insolation changes drive responses in simulated genesis potential index across the five models (Figure 3). The magnitude of the response in all models is similar. HadCM3 and MIROC-ESM show a widespread reduction of genesis potential in the northern hemisphere compensated for by an increase in the southern hemisphere. The response of IPSL-CM5-LR and CCSM4 bear similarities to each other in that their bands of GPI in the North Pacific become more zonal (as visible by the dipole patterns in Fig. 3).

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The ensemble genesis potential for the mid-Holocene (Figure 4a) shows a largely similar distribution as the preindustrial period (Figure 2f), although a broadly coherent pattern of GPI change is observed (Figure 4b). The southern hemisphere exhibits a weak increase in GPI from mid-Holocene over preindustrial, except for pockets around Northern Australia that show a stronger increase. A northward shift in GPI is noticeable in the eastern North Pacific, unsurprisingly associated with the local shift in ITCZ. This shift in the ITCZ would be expected to not only impact the genesis of storms (Merlis et al, 2013) but also their intensity (Ballinger et al, 2015). A slight decrease in genesis potential is seen in the North Atlantic.

There is a good agreement across the ensemble on the sign of the mid-Holocene change in most areas amongst the five GCMs (Figure 4c). There is a general decrease in GPI in the northern hemisphere, and an increase in GPI as one moves polewards in the southern hemisphere. Although several regions show strong agreement for increased GPI, such as the South-East Pacific and South Atlantic, these are regions of minimal cyclone occurrence at present (Knapp et al., 2010) and should not be interpreted as having storms in the mid-Holocene.

The results for the mid-Holocene using these PMIP3 models bear strong similarities with findings from Korty et al. (2012b) that detail cyclone genesis potential using an ensemble from ten GCMs from PMIP2. The magnitude and distribution of genesis potential share similar patterns across all oceans. Nonetheless this study simulates a slightly weaker genesis potential for the western South Indian Ocean and the South Atlantic, as well as a slightly weaker increase in genesis potential for mid-Holocene over preindustrial in both hemispheres. The model agreement (Figure 4c) is also similar to that of Korty et al. (2012b) with both showing an anvil shape area of reduced GPI in the central North Pacific.

4.4 Last Glacial Maximum (LGM)

During the LGM, the tropics experienced cooling of −5 °C to −2 °C over land, while most of the tropical surface ocean did not encounter cooling beyond −2 °C especially in the southern hemisphere (Waelbrook et al. 2009). The LGM mean tropical SST from the five GCMs in this

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study during the peak storm period is 2.0 °C cooler than preindustrial. Simulated genesis potential responses for the LGM show both variations spatially and across the ensemble (Figure 5). CCSM, HadCM3 and MIROC show generally stronger genesis, while FGOALS and IPSL show a weakening in genesis potential relative to preindustrial. All of the models show some form of compensation, indicative of shifts in the relative dominance of the TC formation locales.

The ensemble genesis potential for the LGM (Figure 6a) shares again, at a first glance, a similar distribution with the preindustrial. However, it exhibits greater intensity of genesis potential in the central North Pacific and near the SPCZ (Figure 6b). The central-eastern South Indian Ocean shows decrease in genesis potential along 10°S, whilst the South Pacific sees an increase. Some of this shift in GPI is related the increased land exposure in the Maritime continent at the LGM – a feature that is treated somewhat differently between the models (observe the land masks in Fig 5). There are slight decreases of genesis potential observed in the North Atlantic.

There is some model agreement (Figure 6c) focussed around the largest changes in genesis potential in the LGM period for most oceans relative to preindustrial. The North Atlantic exhibits a very robust decrease in genesis potential that spreads over Central America into the eastern North Pacific. This is likely a response to the imposition of the Laurentide ice sheet and its impact on the regional circulation. There appears to be a dipole pattern in the Indian Ocean (most noticeable in Figure 6c), although it is not as robust. This is likely an expression of the alteration in Walker Circulation (DiNezio et al, 2011), whose fidelity varies across models depending on their parameterisations and boundary conditions (DiNezio and Tierney, 2013). These patterns of the model agreement are qualitatively similar to those seen in the PMIP2 experiments (Korty et al. 2012a), yet show more consistency across the ensemble.

4.5 Pliocene

The Pliocene is a warmer climate compared to preindustrial (Dowsett et al, 2010; Haywood et al., 2013), with the area-averaged tropical SST from the five GCMs in this study over the peak storm season being 1.7 °C warmer. In terms of the GPI difference from preindustrial

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(Figure 7), most models suggest a mixed response in the direction of change for various oceans, apart from MIROC that shows only a limited change. The majority of models indicate a decrease in genesis potential for the North Atlantic and South Indian oceans. In the North Pacific Ocean, the majority of models suggest a decrease in genesis potential in the eastern development region, but appear to have mixed responses for the western region and the SPCZ.

As for the preindustrial, the conditions most favourable to cyclone genesis in the Pliocene ensemble mean can be found in the eastern and western areas of the North Pacific, the SPCZ and central region of the South Pacific, as well as the north-western corner of the South Indian Ocean (Figure 8a). In terms of the difference in genesis potential between the Pliocene and preindustrial periods (Figure 8b), the North Atlantic, North Pacific, and South Indian oceans and the SPCZ region experience a decline in favourable cyclogenesis conditions. It is worth noting that HadCM3 simulates a reduction in GPI for nearly all regions of observed cyclogenesis (Figure 7c).

This large-scale pattern appears to be robust as most models suggest a general decrease in genesis potential for the Pliocene relative to the preindustrial for most oceans (Figure 8c), although the magnitude of change might be small in areas - such as the South Atlantic and eastern South Pacific. There appears to be weaker model agreement on the sign of change for the subtropical latitudes for the Pacific and Indian oceans in both hemispheres, although a slight increase in genesis potential may be expected.

4.6 Genesis Frequency

Figure 9 illustrates the cumulative annual, global genesis potential index generated from the five GCMs across the various palaeoclimates as a percentage of the preindustrial. Remember each preindustrial GPI field is normalised such that this sum equals 90 – roughly akin to the observed number of storms formed each year. The ensemble-mean annual, global totals for the Pliocene, LGM and mid-Holocene are determined to be 89%, 97% and 101% of the preindustrial respectively.

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Estimating the natural variability (or more strictly 'internal variability') of an ensemble mean number is problematic. As a pragmatic measure, we take that of the model with the highest internal decadal variability (HadCM3) - giving a standard deviation (σ) of 2.9%. Given that the ensemble cumulative values are generally within the standard measure of 2σ (Haywood et al. 2013), the cumulative GPI for both the LGM and mid-Holocene is considered to have not deviated significantly from the preindustrial era. Whilst the ensemble mean value for the Pliocene is statistically significant by this metric, in fact the magnitude of the reduction is driven primarily by the HadCM3 member (the ensemble average without it is 98% of the preindustrial). The assumption of a Gaussian distribution inherent in this metric of significance is clearly not valid for this ensemble. It is therefore not clear we can consider the reduction seen in Pliocene ensemble as robust feature. This is especially true in light of the uncertainty in the internal variability measure itself discussed in section 2.2.

In Figure 10, the northern hemisphere peak in JASO appears consistent across the various epochs, as does the southern hemisphere's peak in JFMA. This justifies the choice of the peak storm seasons for the respective hemisphere as presented here. Previous work from Korty et al. (2012a, b) using PMIP2 data showed a stronger peak from the southern hemisphere relative to the north, while this study suggests a stronger northern hemisphere peak. This suggests that the PMIP3 simulations may have improved accuracy in describing present day trends of northern hemisphere for conditions more conducive for cyclone genesis (Gray 1968; Klotzbach 2006; Webster et al. 2005).

Korty et al. (2012a) found a slight increase in cumulative GPI at the LGM in the previous generations of models. This ensemble shows a marginal reduction in this metric, yet there is substantial spread between the models themselves (Fig. 9). The reduced TC genesis potential index associated with the warm Pliocene conforms to the Knutson et al. (2010) view of future behaviour. It does differ from the sole prior Pliocene TC study (Fedorov et al 2010), both in results and approach. A discussion of the two pieces of work follows in section 5.1.

For the mid-Holocene epoch, a salient increase in October activity is observed by Korty et al. (2012b), which has been attributed to a delayed SST response from the TOA insolation

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forcing, resulting in a shift of the northern hemisphere storm season. However, such a feature is not observed in this study. Annual SST changes are found to have varied minimally relative to the preindustrial (Figure 1), suggesting that the ocean component during the mid-Holocene may play a lesser role in comparison to the Pliocene and LGM epochs where more substantial SST changes are observed.

5 Discussion

During the Pliocene and LGM, changes in carbon dioxide led to sea surface temperature (SST) changes throughout the tropics, yet the potential intensity of TCs are observed to be relatively insensitive to these changes (Figure 1). The cumulative genesis potential index (taken as proxy for global storm numbers per year) is likewise found to be fairly consistent across the various palaeoclimates. Despite disagreement about the change of global annual TC frequency (Figure 9), there is some model consensus on the spatial patterns of tropical cyclogenesis change. These changes may be attributable to changes in large scale atmospheric properties such as carbon dioxide levels, altered topography and orbital forcing.

The key difference in forcing between the mid-Holocene and preindustrial lies in the orbital parameters (Table 1). Solar insolation received in the northern hemisphere is enhanced relative to the southern hemisphere as a result of the altered precession (Braconnot et al. 2007). There is a slight tropospheric warming in the northern hemisphere for the middle and high latitudes as a consequence of this, while general tropospheric cooling is found in the tropical region and the southern hemisphere. Increased TC genesis is observed during the mid-Holocene in the southern hemisphere, along with slight reduction in the northern hemisphere (Figure 4c). This is associated with higher entropy deficit in the northern hemisphere which would act to hinder cyclone genesis compared to the southern hemisphere (not shown) as found by Korty et al. (2012b). The potential intensity increases very slightly at all latitudes (not shown).

Carbon dioxide, being a well-mixed greenhouse gas, causes globally coherent temperature changes in contrast to orbital forcing. The Pliocene represents a period of elevated carbon dioxide concentration resulting in a warmer climate relative to the preindustrial period, while

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the LGM era experienced an opposite cooling effect arising from lower carbon dioxide levels present at that time. Korty et al. (2012a) emphasise the fact that conditions at the LGM remain roughly as favourable as the preindustrial for tropical cyclones. They discuss the slight increase in favourably brought about local changes in the entropy deficit and wind shear terms in PMIP2. The most robust changes in GPI in the present ensemble occur in the Atlantic and appear stronger than found by Korty et al. (2012a). The ultimate cause of this difference is likely the inclusion of altered ice-sheets in the PMIP3 vs PMIP2 experiments (Abe-Ouchi et al., 2015). This results in a small cooling of SSTs (>0.5 °C) stretching from the Caribbean to West Africa and consequently a change in potential intensity that less is than seen by Korty et al. (2012a).

In response to the greenhouse gas driven warming seen in the Pliocene experiments (Hill et al., 2014), a general decrease is observed in genesis potential in the convergence zones in both the northern hemisphere and southern hemispheres (Figure 7, 8b). The PlioMIP simulations have a weaker Hadley and Walker circulation that results in a broadening of the Inter-tropical Convergence Zone (ITCZ; Contoux et al. 2012). Kamae et al. (2011) show that Equatorial specific humidity increases in the lower troposphere and decreases in the mid-troposphere arising from a weakened ascent of the Walker circulation in the PlioMIP simulations. Convective processes are curtailed leading to an associated increase in moist entropy deficit (not shown) which leads to the general decrease in GPI within the Pliocene simulations.

5.1 Possible sea surface temperature biases and missing feedbacks

Prior work looking at tropical cyclones in the Pliocene (Fedorov et al., 2010) shows a rather different behaviour than that found here. The two studies approach the Pliocene climate and its tropical cyclones from alternate standpoints. By summarising both approaches, we hope here to allow readers to consider their respective merits.

Fedorov et al. (2010) start with proxy SST observations from the early Pliocene (~4 Ma), which imply much weaker tropical SST gradients both meridionally (Brierley et al., 2009) and zonally (Wara et al., 2009). Although there has been some criticism of the palaeothermometers (O'Brien et al., 2014), this does not affect the estimates of reduced SST

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gradients (Brierley et al., 2015). Coupled climate models seem unable to replicate this climate state (Fedorov et al., 2013). Fedorov et al. (2010) use a atmosphere-only model driven by a prescribed 'Pliocene' SST field (Brierley et al., 2009) to create inputs for a statistical-dynamical downscaling model (Emanuel et al., 2008). The statistics of the tropical cyclones directly simulated by the downscaling model were analysed and show a substantial increase of tropical cyclones across the globe. Fedorov et al. (2010) then focus on the increase in the central Pacific and suggest that these storms could be part of a feedback that maintains the weak zonal SST gradient on the Equator.

This study uses simulations from the PlioMIP experiment that aims to investigate systematic biases between the palaeobservations and modelled climates of the Pliocene (Haywood et al. 2011). This experiment focuses on ~3 Ma and finds many similarities on global-scale (Haywood et al, 2013). There are some regions with substantial mismatch across the ensemble however, most notably the high latitude North Atlantic and Tropical Pacific. As a whole this ensemble does not show any change in the zonal SST gradient, something true of every model in the subset used here (Brierley 2015). Aside from the limitation of using a genesis potential index, the present study may therefore include a systematic bias in its representation of the Pliocene - although it has been suggested (e.g. O'Brien et al., 2014) that in fact the palaeobservations are in error. Nonetheless it is interesting that the present study shows an increase in genesis potential in the central Pacific – impinging on the subduction zone critical for the cyclone-climate feedback discussed by Fedorov et al. (2010). Should cyclone-cliamte feedbacks be an important feature of the actual Earth System, then systematic biases would exist across all the simulations presented here, not only the Pliocene ones.

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5.2 Relationship to future projections

Records do not currently exist to either confirm or refute the potential of the atmospheric conditions simulated by this ensemble for tropical cyclogenesis. They probably never will. Yet the Earth will shortly experience carbon dioxide concentrations beyond those of the Pliocene period. Therefore, it is interesting to consider how the results above correspond to future projections. One further motivation to do this is that the palaeoclimate simulations are all equilibrium experiments, whilst the future projections are transient. It is therefore anticipated that the climate change signal will be easier to detect in the palaeoclimate

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simulations. In transient simulations, large scale forcings may not fully account for the observed variability (Menkes et al. 2012), as stochastic effects may potentially account for up to half of the observed variability (Jourdain et al. 2010).

The RCP8.5 scenario is used to project how GPI may develop in future. It is chosen as it is the most extreme scenario and so should have the biggest signal. In this scenario, carbon dioxide concentrations reach 936ppmv by 2100 (Collins et al., 2013), more than double the level in the Pliocene simulations.

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The GCMs selected in this study all show future changes in tropical cyclone count (at least as estimated by the cumulative GPI) under the RCP8.5 transient scenario (Figure 11). Yet these trends are not consistent between the models. Note that HadCM3 has not contributed results for RCP8.5, so a later generation of the model (HadGEM2) has been substituted. Two models suggest an increase in cumulative GPI, while three models suggest a decrease, resulting in an ensemble mean with a trend of slightly reduced cumulative GPI by 2095. The future response is also seemingly inconsistent with the palaeoclimate responses in the same GCM. For example, MIROC shows a decrease in the warm Pliocene and an increase during the LGM: counter-intuitively is also shows an increase under RCP8.5. Efforts to detect obvious relationships in across the ensemble – for example between North Hemispheric temperatures and cumulative GPI – were unsuccessful (not shown).

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Interestingly, the multi-model mean GPI difference between the future RCP8.5 (2071–2100) scenario and historical (1971–2000) simulation from Camargo (2013) shows an opposite pattern to the equilibrium Pliocene-control difference in Figure 8b of this study. The transient RCP8.5 GPI difference in Camargo (2013) suggests a global increase (except for a small area in the central South Pacific where a decrease is expected). Meanwhile the equilibrium Pliocene-preindustrial difference in this study shows a general decrease (except for a region of the central North Pacific that has an increase in GPI). The stark difference in GPI response between the RCP8.5 and Pliocene therefore throws additional questions on the suitability for the choice of the Pliocene as a projection of modern day greenhouse climate (Haywood et al., 2009), at least in terms of cyclogenesis-related measures. Held and Zhou (2011) show that

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TCs respond differently to the forcing directly and the resultant temperature changes. This may mean that the equilibrium climates simulated by PMIP should not be compared to the transient states driven by the future scenarios.

Emanuel (2013) downscaled six CMIP5 GCMs for the RCP8.5 projection, and concluded that an increase in future global tropical cyclone activity might be expected. The same paper also acknowledged that other modelling groups obtained contrasting results where modest decreases (Knutson et al. 2010) and no robust change (Camargo 2013) in future tropical cyclone activity had been detected. Emanuel (2013) and Camargo (2013) both supplement their direct measures of cyclogenesis with analysis of GPI that supports the directions of the changes found. Two models (CCSM4 and HADGEM2-ES) that Emanuel (2013) used for the RCP8.5 scenario are also incorporated in this study, but a decreasing trend is not detected for the two particular models here. Possible reasons that could account for the difference include the use of a modified “clipped” vorticity GPI in this study, and a different choice of 250-850 hPa tropospheric wind shear in Emanuel (2013). The striking difference in genesis potentials, despite a similar GCM choice, suggests that the GPI may be highly sensitive to slight adjustments in the diagnostic definition.

Kossin et al. (2014) showed that the lifetime-maximum intensity of tropical cyclones is migrating polewards at a rate of about one degree of latitude per decade, similar to the rate of expansion of the tropics (Lucas et al. 2014). No coherent message about poleward expansion of conditions favourable for cyclogenesis was found in this ensemble (not shown) and changes in GPI are found largely in the 10°-20° region of both hemispheres, with minimum adjustment in the sub-tropics.

6 Conclusions

The cumulative global, annual genesis potential index (a proxy for global tropical cyclone frequency) is found to have been relatively constant over the range of past climates. This range encompasses both greenhouse (Pliocene) and icehouse (Last Glacial Maximum) climates and changing orbital forcing. These conditions are thought to represent the extremes of climates Earth has experienced in the past three million years. Often the members of the

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multi-model ensemble do not agree on the sign of the global change (Figure 9), leading to high uncertainty on this headline metric.

The ensemble shows much higher levels of consistency on the regional scale, however. All five models agree on less potential for cyclogenesis in the North Atlantic at the Last Glacial Maximum. This is compensated for by an increased potential for cyclogenesis in the central North Pacific, to a greater or lesser degree. This is a circulation response to the existence of a large ice-sheet over North America. A qualitatively similar feature has been seen previously (Korty et al., 2012a), but with some dependency on the ice-sheet imposed (Abe-Ouchi et al., 2015). Obviously the reverse of such pattern would not be expected in future. The mid-Holocene ensemble shows alterations of GPI associated with shifts in the intertropical convergence zone driven by the altered incoming solar distribution. Again the results from this ensemble are qualitatively similar to those from prior model ensembles (Korty et al., 2012b).

One motivation for studying past climate tropical cyclone response was to investigate its relationship to future projections. The genesis potential under the RCP8.5 scenario was computed and contrasted with the palaeoclimate response. There is no simple relationship that emerges between cumulative GPI and global temperature. This result implies that changes in global frequency of tropical cyclones remains much less robust than regional responses. The conclusion is further strengthened by the apparent sensitivity of projected future global frequency to the precise genesis potential index used – with our analysis not fully supporting either the results of Emanuel (2013) nor the opposing results of Camargo (2013) despite all three using the same simulations.

Acknowledgements

The work was made possible through a scholarship awarded to J.H.K. from PUB, Singapore’s National Water Agency. The authors thank Suzana Camargo for her useful comments on GPI metrics and Kerry Emanuel for his assistance, not least his release of the Potential Intensity matlab routine. The assistance of Fran Bragg, Camille Contoux, Wing-Le Chan and Weipeng Zheng was essential to procure the necessary Pliocene simulation files. The creation of

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Tables

Table 1. Trace gases and Earth's orbital parameters recommended for PMIP. The precession is specified with respect to NH autumnal equinox.

Period	CO_2 (ppmv)	CH_4 (ppbv)	N_2O (ppbv)	Eccentricity	Obliquity (°)	Angular Precession (°)
Pliocene (3Ma)	405	760	270	0.016724	23.446	102.04
LGM (21ka)	185	350	200	0.018994	22.949	114.42
mid-Holocene (6ka)	280	650	270	0.018682	24.105	0.87
Preindustrial (Control)	280	760	270	0.016724	23.446	102.04

Table 2. List of GCMs used in this study. The *b* factor in the right column is incorporated in the GPI such that preindustrial control TC genesis frequencies are calibrated to 90 annual occurrences for each GCM. HadGEM2-ES and MIROC4m are only used for the single time periods as indicated. The preindustrial simulation in PlioMIP for HadCM3 shows different behaviour that that of the PMIP simulations and so requires a different normalisation factor, *b*.

Model	Atmospheric Resolution °Lat x °Lon x Levels	*b* ($x10^{-5}$)	Standard Deviation (%)	Reference
CCSM4	0.9 × 1.25 × 26	6.2	1.7	Gent et al. 2011
FGOALS-G2	2.8 x 2.8 x 26	2.7	1.1	Li et al. 2013
HADCM3 (PlioMIP value)	2.5 × 3.75 × 19	5.8 (1.5)	2.9	Gordon et al. 2000
HADGEM2-ES (RCP8.5 only)	1.25 x 1.875 x 38	2.7	-	Collins et al. 2011
IPSL-CM5A	3.75 ×1.875 × 39	2.4	1.6	Dufresne et al. 2013
MIROC-ESM	2.8 × 2.8 × 80	1.6	2.5	Sueyoshi et al. 2013
MIROC4m (Pliocene only)	2.8 × 2.8 × 20	0.8	-	Chan et al. 2011

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7 Figures

Figure 1. Sea surface temperature (contour lines) and potential intensity in northern hemisphere (NH) during Jul-Oct (JASO) and southern hemisphere (SH) during Jan-Apr (JFMA) for (a) preindustrial control, (b) Pliocene, (c) LGM and (d) mid-Holocene. Units are SST (°C) and potential intensity (ms^{-1}).

Figure 2. Preindustrial control GPI from (a) CCSM4, (b) FGOALS-G2, (c) HadCM3, (d) IPSL-CM5A-LR, (e) MIROC-ESM and (f) the Ensemble Mean. Northern hemisphere depicts JASO monthly mean GPI while southern hemisphere depicts JFMA monthly mean GPI. Units are 10^{-13} normalised occurrences m^{-2} $month^{-1}$

Figure 3. Cyclone genesis difference between mid-Holocene and PI in northern hemisphere (JASO) and southern hemisphere (JFMA) for (a) CCSM4, (b) FGOALS, (c) HadCM3, (d) IPSL, (e) MIROC. Units are 10^{-13} normalised occurrences m^{-2} $month^{-1}$

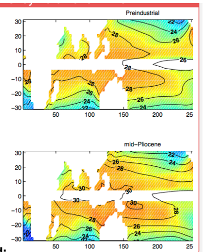
Figure 4. (a) mid-Holocene ensemble GPI (b) mid-Holocene and preindustrial control ensemble GPI difference, and (c) Robustness of the palaeoclimate genesis signals, as indicated by the number of models agreeing with the direction of the change. Yellow and red denote areas for model agreement on positive sign change. Green and blue areas denote model agreement on negative sign change. Northern hemisphere depicts JASO season, while southern hemisphere depicts JFMA season. Units in (a) and (b) are 10^{-13} normalised occurrences m^{-2} $month^{-1}$.

Figure 5. Cyclone genesis difference between LGM and preindustrial in northern hemisphere (JASO) and southern hemisphere (JFMA) for (a) CCSM4, (b) FGOALS, (c) HadCM3, (d) IPSL, (e) MIROC. Units are 10^{-13} normalised occurrences m^{-2} $month^{-1}$

Figure 6. (a) LGM ensemble GPI (b) LGM and preindustrial control ensemble GPI difference, and (c) Robustness of the ensemble signals, as indicated by the number of models agreeing with the direction of the change. Yellow and red denote areas for model agreement on positive sign change. Green and blue areas denote model agreement on negative sign change. White areas denote regions where less than four models agree. Northern hemisphere depicts JASO season, while southern hemisphere depicts JFMA season. Units in (a) and (b) are 10^{-13} normalised occurrences m^{-2} $month^{-1}$.

Figure 7. Change in genesis potential index between Pliocene and preindustrail in northern hemisphere (JASO) and southern hemisphere (JFMA) for (a) CCSM4, (b) FGOALS, (c) HadCM3, (d) IPSL, (e) MIROC. Units are in 10^{-13} normalised occurrences m^{-2} $month^{-1}$

Figure 8. (a) Pliocene ensemble GPI (b) Pliocene and preindustrial control ensemble GPI difference, and (c) Robustness of the ensemble signals, as indicated by the number of models agreeing with the direction of the change. Yellow and red denote areas for model agreement on positive sign change. Green and blue areas denote



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model agreement on negative sign change. White areas denote regions where less than four models agree. Northern hemisphere depicts JASO season while southern hemisphere depicts JFMA season. Units in (a) and (b) are 10^{-13} normalised occurrences m^{-2} $month^{-1}$.

Figure 9. Model and ensemble mean cumulative annual, global genesis potential index as percentage of preindustrial control value.

Figure 10 Northern hemisphere (NH) and southern hemisphere (SH) ensemble monthly GPI integral for (a) Pliocene (b) LGM, (c) mid-Holocene and (d) preindustrial control.

Figure 11. RCP8.5 annual cyclone genesis frequency projection between 2005-2095. The shaded area represents the spread expected from internal variability alone, from the baseline of 90 cumulative occurrences observed in modern day (black dashed line).

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The key difference in forcing between the mid-Holocene and preindustrial lies in the orbital parameters (Table 1). Solar insolation received in the northern hemisphere is enhanced relative to the southern hemisphere as a result of the altered precession (Braconnot et al. 2007). There is a slight tropospheric warming in the northern hemisphere for the middle and high latitudes as a consequence of this, while general tropospheric cooling is found in the tropical region and the southern hemisphere. Increased TC genesis is observed during the mid-Holocene in the southern hemisphere, along with slight reduction in the northern hemisphere (Figure 4c). This is associated with higher entropy deficit in the northern hemisphere hindering cyclone genesis compared to the southern hemisphere (not shown). The potential intensity increases slightly at all latitudes.

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and using a statistical downscaling approach, involved the imposition of a

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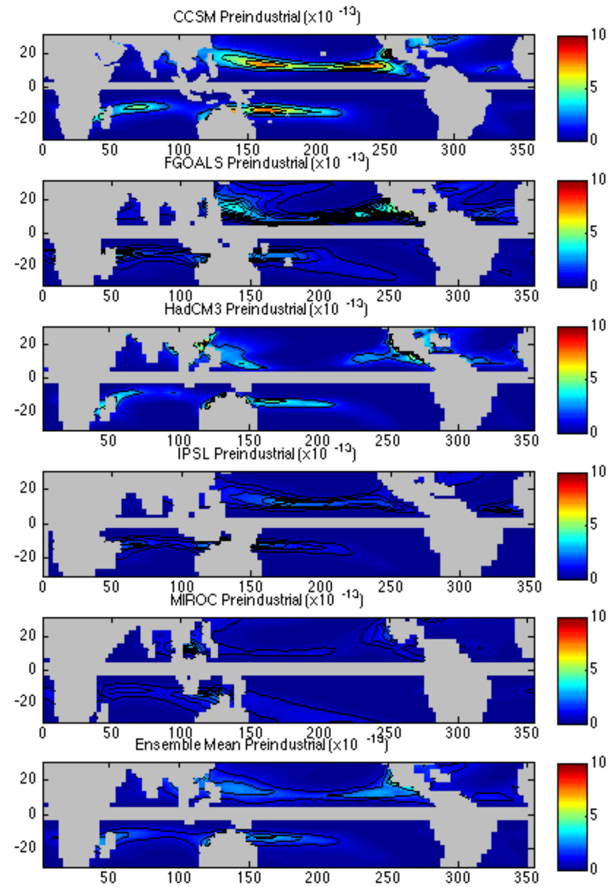

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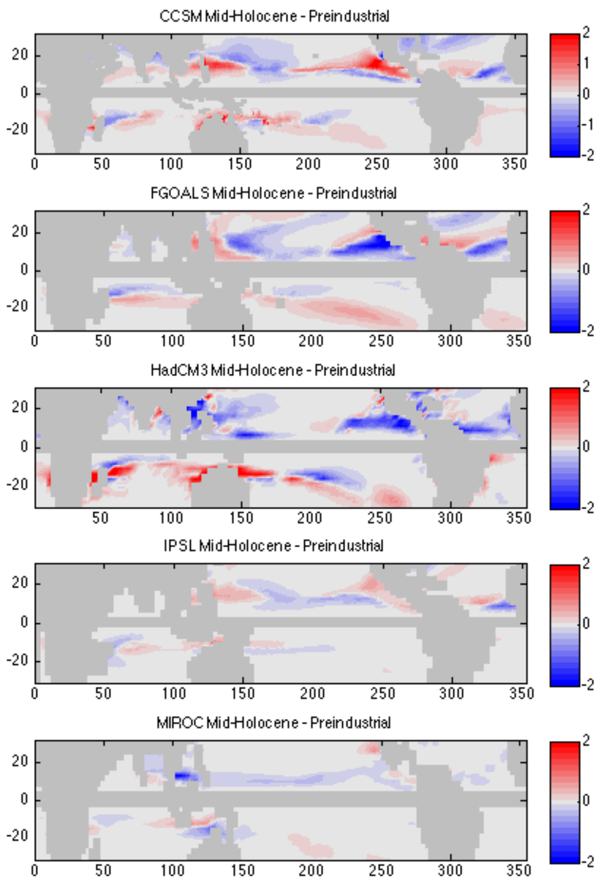

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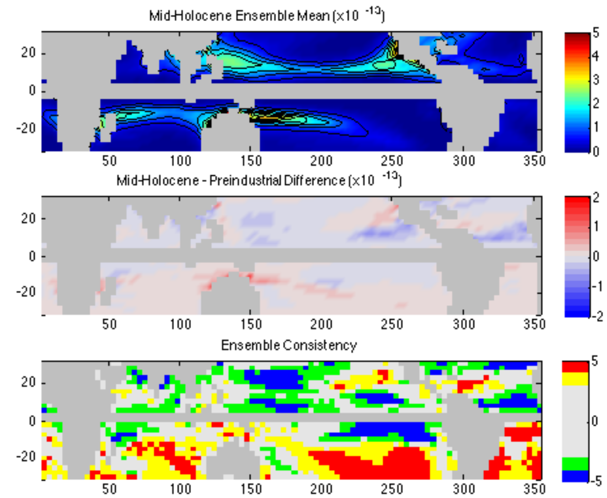

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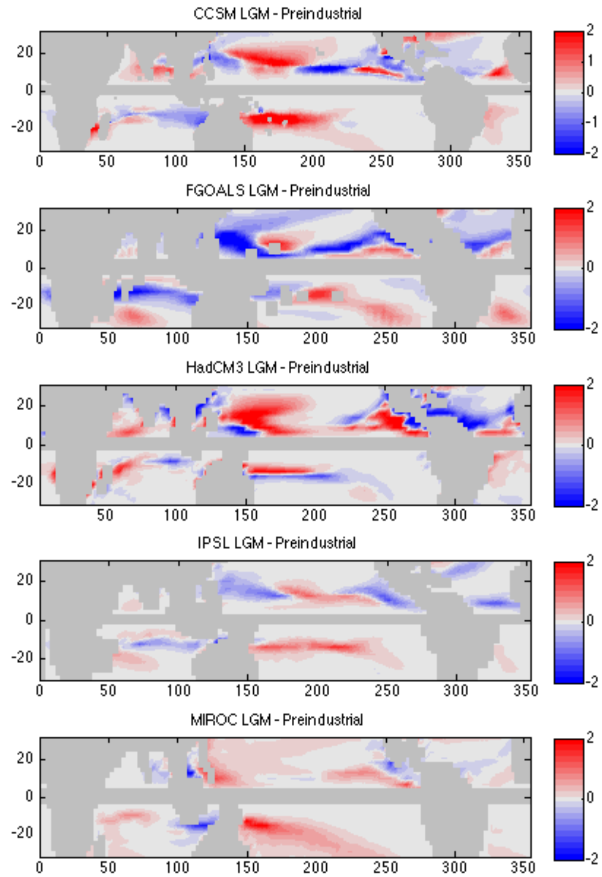

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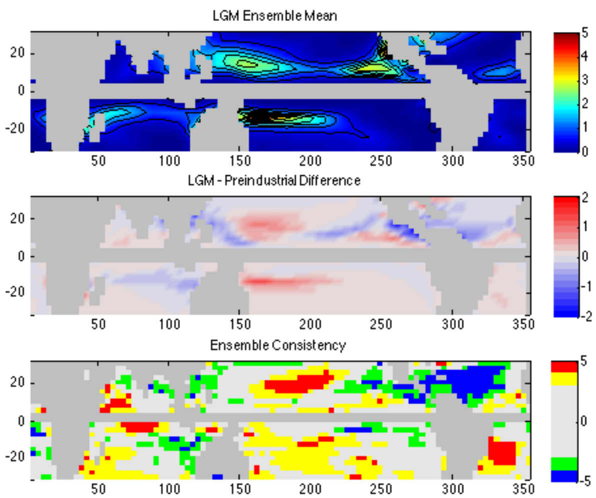

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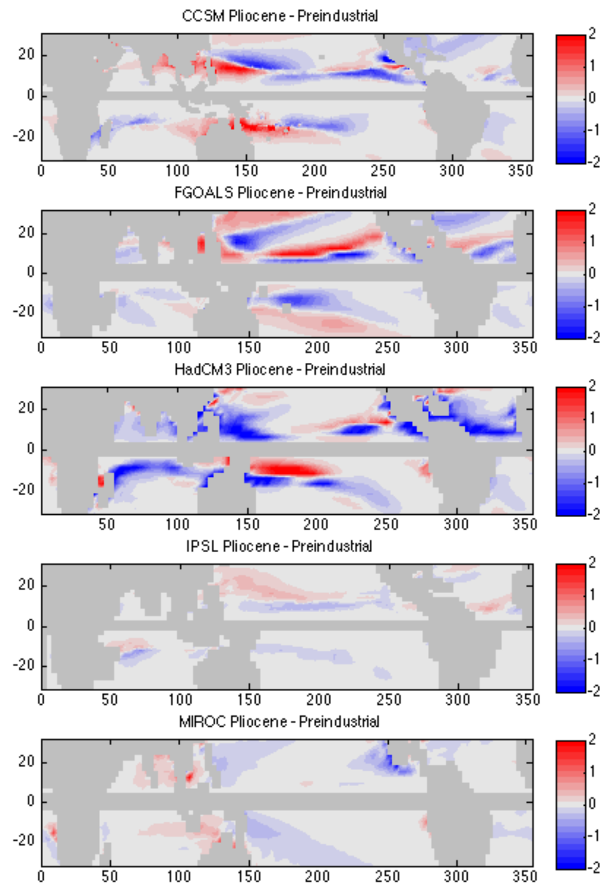

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Cyclone genesis difference

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Cyclone genesis difference

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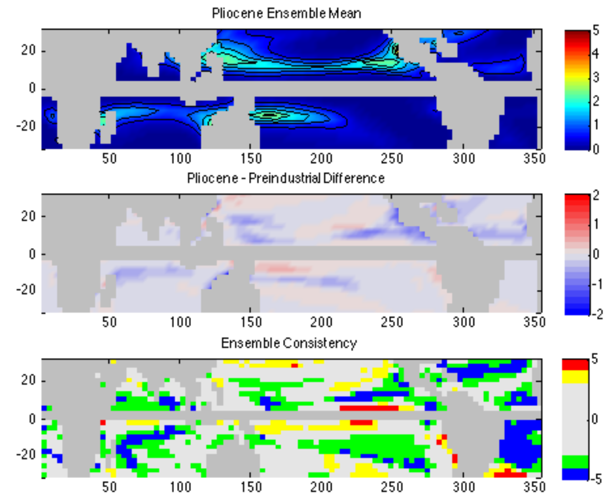

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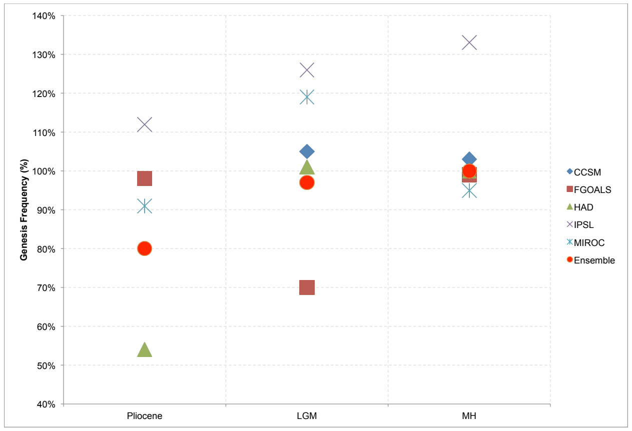

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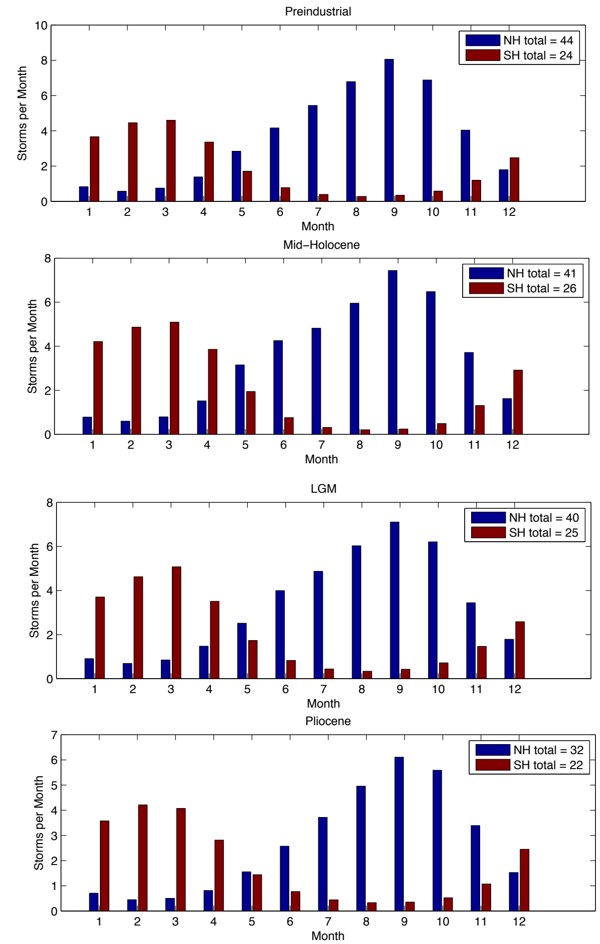

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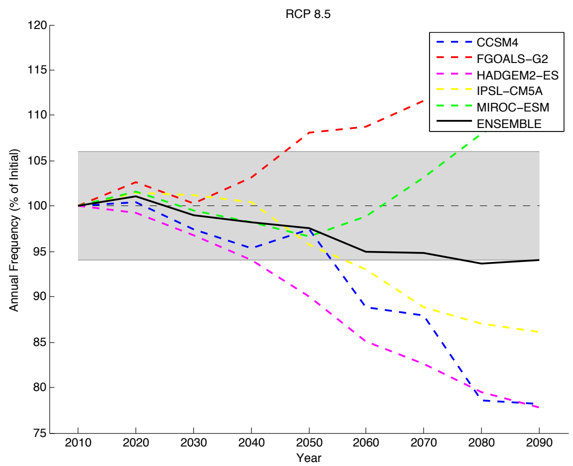
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CCSM4
FGOALS-G2
HADGEM2-ES
IPSL-CM5A
MIROC-ESM
ENSEMBLE
Annual Frequency (% of Initial)
120
115
110
105
100
95
90
85
80
75
2010
2020
2030
2040
2050
2060
2070
2080
2090
Year