Response to reviewers:

R1:

We thank the reviewer for their insightful comments regarding our paper. We acknowledge that the paper is perhaps a little on the long side due to enthusiasm to utilize a range of high-resolution models and exciting new observational data. Because we tried to fit all of this in the reviewer has understandably missed some of the arguments we have made. Following his/her advice we have tightened the paper's structure to better present our arguments. Reviewer comments are in italics.

1) Instead of promoting their view of water vapour flux as the alternative to phase changes as the mechanism for feedback, a more measured judgement that both might be at work would be helpful. I believe the methodology used highlights the role of the WCB but cannot exclude the possibility of the phase change hypothesis due to the strong serial correlation of both through temperature. The authors admit this themselves (page 18, line 33). The largest of all correlations in the entire study is that between WCB and SST, making it very hard to argue one way or the other, so why even try. A less strong but equally important conclusion the paper can draw is that it is likely that the WCB effect needs to be considered as a possible, but perhaps not the only, mechanism.

Please note that throughout the manuscript we do not discount the possibility that the phase transition may be at work – we repeatedly refer to the WCB moisture flux as predicting the majority of the response to transient warming and the decadal trend, not all of it (P1 L33, P4 L7). In fact, the last part of the discussion (section 3.4 of the previous version) centers around investigating the influences of changes in phase using cloud-top phase observations from AIRS.

The reviewer makes a good point that in the context of analysis of covariability we did not sufficiently explain why covariability between SST and WVP via Clausius-Clapeyron isn't a significant issue in inferring the feedback. As the reviewer notes, we were careful to point this out– in fact, it is a central issue in the literature that phase changes and the WCB-driven change in LWP are very easy to conflate if a naïve analysis based on SST alone is pursued. However, the correlation between SST and LWP is very weak (r=0.3 on a cyclone, by cyclone basis). We have added figures showing this. In the original manuscript we looked at dropping each predictor and found that the coefficient relating SST to LWP flipped in sign if WCB was dropped as a predictor (paragraph starting on P18 L32 of the original ms). We have added additional text throughout the manuscript showing that SST is a poor predictor of LWP, even if it is a good predictor of WVP. This is important to thoroughly discuss, especially given that analysis relating LWP to SST alone will give a poor prediction of feedbacks. We thank the reviewer for encouraging us to expand on this.

The reviewer incorrectly points out that our analysis is only based on regression. Our analysis inferring the cloud feedback from the current climate is indeed based on regression. However, following previous work inferring feedbacks from the observational record (Qu et al., 2015) we use modelling simulations of transient warming to test whether these inferences hold when the climate is warmed (AMIP and AMIP+4K). These demonstrate that by using the AMIP WCB-LWP relationship we can predict the majority of changes in cyclone LWP between AMIP and AMIP+4K. Because of length of the MS we had moved most of the figures relating to this analysis to the supplementary material since it seemed like the main result of this section was to affirm that the relationship between LWP and WCB in the present can predict the future. To better respond to the reviewer's argument we have rewritten portions of the main text to clarify our arguments and separated our discussion into sections that compartmentalize this analysis so that the reader can better follow the argument. Figures that are not essential to the story have been removed from the main text. Essential figures that were in the SM have been moved to the main text. The discussion has been refocused on the SH for clarity (equivalent figures for the NH have been added to the SM).

2) The paper needs to be rewritten and significantly shortened. 26 pages of dense text and 28 figures (including the supplement) is simply too much. Many of the supplementary figures are used for major arguments in the text, so they are anything but supplemental

As noted in the comment above, we have reorganized and shortened the text to better explain our argument, although we note that many of the figures are just repetitions of the same figure for different regions so they are not entirely new figures to digest and we were just showing them to try and be thorough. We have refocused on the Southern Ocean and moved equivalent NH figures to the SM.

3) The methodology of linear regressions, which is used to make major arguments about processes, is insufficient. Take as an example equation 4. Not only are the two predictors highly correlated, but the physical arguments surrounding them are flawed. Whilst in PBL clouds it is sensible to assume that the cloud temperature is strongly coupled to the SST, I fail to see why this would be true in extratropical cyclones. Furthermore the very old idea the LWP is simply a function of temperature has been discarded for a while now. Not surprisingly then, the method reveals that almost all of the relationship resides in the first term, which turns out to be mainly due to water vapour increases directly tied to temperature increases, which themselves prohibit you to exclude phase change effects. This highly circular argument makes it very hard to support that rather strong conclusion that it "appears that once WCB moisture flux is accounted for relatively little room is left for an effect related to phase changes." (page 19, line 6). We simply don't know. What we have learned is that phase changes alone might be too simple an explanation. Nothing wrong with that as a conclusion.

Please see our response to the reviewer's point one. Our analysis of transient warming simulations supports our analysis of covariability within the current climate. We have added additional analysis to the text showing that SST is not a good predictor of cyclone LWP. We have proposed a simple mechanism based on the moisture flux. We have found that this mechanism can predict the majority of the observed trend in response to the warming of the Southern Ocean and can predict the majority of the response to increasing SST by 4K in GCMs. The SST is not a perfect analog for temperature in cloud, but once you remove the contributions from the WCB moisture flux, there is very little room left over for the mixed-phase cloud feedback.

4) The averaging over the cyclones is inadequately explained. Page 11, line 10 states that cyclone means are within 2000 km of the cyclone centre. Is this applied to every cyclone? Doesn't it matter how big the cyclone is? Does within mean that sometimes it's less? If the cyclone mean is always 2000 km from the Centre, couldn't this introduce artefacts? If the cyclones are smaller than 2000 km and their size changes, this will change all the averages with little relation to the flux, would it not?

The average is the mean within 2000km and is not altered as a function of cyclone structure. This technique is common in the literature and is explained in the cited papers and in the methods of this and the previous version of the article (Field et al., 2011;Field et al., 2008;Field and Wood, 2007;Bodas-Salcedo et al., 2016;Bodas-Salcedo et al., 2012;Bodas-Salcedo et al., 2014). It is not clear what the benefit of a more complex methodology would be in the context of examining the relationship between WCB moisture flux and LWP in cyclones. To acknowledge that this is not the only way that cyclone compositing can be achieved we have added the sentence: "More complex analysis techniques exist that allow the definition of the edge of a cyclonic system(Pfahl and Sprenger, 2016)."

5) The paper needs shortening. This can be achieved in several ways, first and foremost by removing the many long paragraphs of indulgent musings and speculations scattered throughout the results section. They really get in the way of your argument and they should be removed and a short (!) discussion section added after the results instead. Almost every time an interesting result emerges, the reader gets distracted with a paragraph of discussion, sometimes not even strongly related to the results. Sometimes those paragraphs precede new results, making them even more confusing. Here are the most prominent examples for this

We have shortened and rewritten the paper to better showcase our argument. Unfortunately, there seems to be some issues with the page numbering in the reviewer's copy and it is hard to follow what page they are looking at. However, we have tried our best to streamline the paper.

Page 5, Line 5-15: A long paragraph with the figure relegated to the supplementary material. Do we really need this?

Please note that this is just the methodology for compositing in the paper as shown at: https://www.atmos-chem-phys-discuss.net/acp-2018-785/acp-2018-785.pdf

Page 14, Line 17-20: What has this to do with what follows? It's just confusing the reader.

As noted above, there seems to be an issue with the page numbering in the reviewer's copy. In the official copy provided by Copernicus this is just a discussion of our choice to use linear regression instead of the exponential fit used in our previous paper(McCoy et al., 2018).

Page 15, Line 8-18: Pure speculation. Not a result, so why is it in the results section?
Page 15, Line 23-35: Ditto

It was too weak to start this paragraph with 'It is interesting to speculate.' It is more than speculation. In McCoy et al. (2018) we showed that if cloud droplet number concentration (CDNC) was included as a predictor it substantially increased the variability in cyclone LWP that was explained. The focus of this paper is the WCB moisture flux so we have dropped the CDNC as a predictor so we can compare across more models. However, the difference in explained variance between basins is consistent with variance in CDNC. We have changed the text to clarify that this is not wild speculation and have shortened this section.

Page 16-17, Line 18-5: Again, this has nothing to do with results and simply distracts from them
We feel that because our results center on the relationship LWP=a*WCB=a*(k*WVP*WS) we need to at least discuss how WS changes in extratropical cyclones. This is a much more complex question than changes in WVP (which is just Clausius-Clapeyron) so we have added this paragraph to discuss the existing scholarship in the field. In the revised manuscript we have cut down the paragraph for brevity.

Page 18, Line 7-8: A very strange sentence. What does this refer to? The un-initiated reader has no idea why this needs yo be discussed. Please revise.
This sentence has been rewritten. It was just to make it clear that a trend within this data set (although not composited) has already been shown in the literature.

Page 18, Line 11-16: What is this paragraph trying to say? What is it referring to? The previous paper? A figure (7) in this paper? I found it hard to make sense of. Please explain what you are doing, then what your result is. Leave the discussion for a discussion section

This is referring to Figure 7 of this paper. We have rewritten the paragraph to clarify it further. It shows that the trend in LWP within cyclones across the SH agrees with the trend in the zonal-mean LWP shown in (Manaster et al., 2017).

Page 19, Line 12-22: Another distracting paragraph of discussion.
We feel that in order to contrast our result to previous work that is not subset to cyclonic regimes we need to have some discussion of what is happening in anti-cyclones. While we appreciate the reviewer trying to help us streamline our paper, we also worry that other readers within the cloud feedback community will want it clarified how our work fits into the existing literature that is not focused on cyclones.

Page 24, Line 1-14: Ditto

Based on comments from this reviewer and reviewer 2 we have focused on the SH in the main text of the paper. However, the difference between the NH and SH cloud-top phase detections in

AIRS necessitate contrasting these regions. We have added some text explaining why we are making this comparison.

6) Another way to shorten the paper is to move the rather detailed model descriptions in Section 2.3 into an appendix.

Thank you- that is a good idea. These have been moved to the supplementary material.

7) The paper clearly struggles with the use of figures in the supplement. The choice seems almost random and major conclusions are drawn from figures in the supplementary material (as evidenced by many of them mentioned even in the conclusions section). The authors need to revisit all their figures, select the ones that are absolutely necessary for their arguments and omit all others. Which ones will be required will only become clear after the rewrite of the results section, so it is hard to make more concrete suggestions at this stage

As discussed in the response to point 1, we have reorganized the paper to remove unnecessary figures and shift more relevant figures to the main text. The main text focusses on the SH now, but equivalent figures for the NH have been inserted into the SM.

8) The paper switches from global considerations to the SH only and back to global from section to section. I am not sure we learned anything from looking at both hemispheres, so the authors may wish to consider to look at the SH only throughout. This might also tighten the arguments in the paper. One could always include a result from the NH in the discussion section if needed, but keep the main results to one hemisphere.

This is a good suggestion. We have moved the NH results to the supplementary material as they support our results in the SH.

Page 5, line 14: You did not state how you composite. Presumably by overlaying the cyclone centers?

Data is averaged onto an equal area grid centered on the center of the cyclone- following (Field and Wood, 2007) as cited in the methodology. We have added a sentence to this effect.

Page 5 line 24: The "observations" are presumably a reanalysis - this needs mentioning here.

Changed title to observations and reanalysis.

Section 2.2.2: I suggest to move this sentence into the composite section. It is needed there and hardly warrants its on subsection anyway. Also, are daily means good enough to do the cyclone detection? Also, the satellite daily means aren't really daily means. Does this matter? Please discuss this.

To follow the structure of the section and allow the reader to quickly see what data sets we are using we will keep it as is. It is unclear what the reviewer means by 'good enough'. In (McCoy et al., 2018) we found reasonable-looking cyclone composites and in that study and the present study we have found strong relationships between moisture flux and rain rate. It is a good point that because of its limited overpasses AIRS is not diurnally-averaged as MAC-LWP and CERES are. This was discussed in the original text (P6 L30), but we have added text further clarifying this to the discussion of cloud-top phase.

"Cloud top phase is measured by the AIRS instrument during the period 2003-2015. It is important to caveat the following analysis by noting that, unlike the other observational data sets used in this paper (MAC-LWP, and CERES), data from AIRS is not diurnally-averaged. It is only available for the Aqua satellite's overpass times. The effects of this temporal subsetting of the data are not clear. However, the goal of the analysis we are pursuing is qualitative. Our intention is to see if liquid cloud phase increases at the expense of ice phase with increasing SST in the same regions that LWP increases with increasing SST. Fig. S15 shows cyclone composited AIRS observations. The structure of ice and liquid phase exhibits a reasonable ice cloud shield and liquid warm sector- indicating that it may shed at least some light on variability in cloud-top phase within cyclones."

Page 7, Line 22-24: Propaganda and not needed here.
Removed.

Page10, Line 11-13: This is confusing. First you say there is a problem with k, then you use it anyway. Is there a justification for this?
These line numbers refer to the UM-CASIM model description, but since your question is generally about using k this seems to be about page 11. We go on to discuss the actual k from the models and the range of k's consistent with the observations. We have added the sentence, 'for consistency with previous literature we have chosen the k based on AMSR-E observations. Our results might change slightly in a quantitative sense if another k was used, but will remain qualitatively the same.'.

Page 11, Line 28-29: This is a strange sentence. What has societal importance to do with WCB being a useful constraint? Nothing I think. Please change this.
The sentence has been reordered to make it clear that societal importance does not make it a key constraint on precipitation. Precipitation is of societal importance and thus WCB moisture flux is a key constraint on the climate.

Page 12, Line 21-22: But isn't it the in-cloud LWP that matters? As the dependence is not linear, we could imagine more rain from lower mean but higher in-cloud LWP through changes in cloud fraction.
Neither the rain rate nor the LWP are in-cloud. We have added some text clarifying this.

Page 12, Line 29: The translation to albedo is also non-linear, and more water does not necessarily mean higher albedo. If we are at high LWP where albedo saturates, further increases in LWP will not change albedo. Please discuss this.
We discussed this at length in our preceding paper(McCoy et al., 2018) as cited on P12 L24 of the original text, but we neglected to add a citation here. We have added a citation to this. Thanks.

Page 14, Line 2-4: In the figure, there aren't many models that flatten more than the observations. On the contrary, there are some that don't flatten at all. So this discussion

is one-sided and needs revising.
We have added 'and vice-versa' at the end of the sentence.

Page 14, Line 15: What is the "climatology" here? Is it the climatology for each month so as to remove the seasonal cycle? If so, say so
It has been noted that the climatology is a monthly-mean climatology.

Page 17, Line 31-32: How can this sentence be true? Are they higher, or are they in good agreement? They cannot be both!
This has been expanded to clarify this.

Page 18 , Line 9: How? Why? Why is any LWP trend equal to a feedback?
Because there is a steady warming signal, a trend over time is probably a response to warming. We have added a sentence to clarify this.

Page 20, Line 5: I don't understand this sentence. What does it mean? Why is it there?
Because we only have AMIP+4K simulations for some of the models. We wanted to clarify why this was. The PRIMAVERA simulations are very expensive and slow to run and the warming simulations will not be done for quite some time. We realize that it is not entirely clear to the reader that there was another part to this paper (testing the predictions from the current climate's behavior in a simulation of a warmed climate, see major comments) and we have reorganized to clarify this. We have also restructured the sections to allow the reader to see the different parts of our argument more clearly.

Page 20, Line 11: This should be the second sentence of the previous paragraph!
It seems more appropriate to leave this sentence where it is as it forms a topic sentence for the following paragraph.

Page 20, Line 26-27: This is and example for a key result with its figure in the supplementary material
As noted above, we have reorganized the paper to make our analysis in the AMIP+4K simulations clearer.

Bodas-Salcedo, A., Williams, K. D., Field, P. R., and Lock, A. P.: The Surface Downwelling Solar Radiation Surplus over the Southern Ocean in the Met Office Model: The Role of Midlatitude Cyclone Clouds, Journal of Climate, 25, 7467-7486, 10.1175/jcli-d-11-00702.1, 2012.

Bodas-Salcedo, A., Williams, K. D., Ringer, M. A., Beau, I., Cole, J. N. S., Dufresne, J. L., Koshiro, T., Stevens, B., Wang, Z., and Yokohata, T.: Origins of the Solar Radiation Biases over the Southern Ocean in CFMIP2 Models, Journal of Climate, 27, 41-56, 10.1175/jcli-d-13-00169.1, 2014.

Bodas-Salcedo, A., Andrews, T., Karmalkar, A. V., and Ringer, M. A.: Cloud liquid water path and radiative feedbacks over the Southern Ocean, Geophys. Res. Lett., n/a-n/a, 10.1002/2016GL070770, 2016.
Field, P. R., and Wood, R.: Precipitation and cloud structure in midlatitude cyclones, Journal of Climate, 20, 233-254, 10.1175/jcli3998.1, 2007.
Field, P. R., Gettelman, A., Neale, R. B., Wood, R., Rasch, P. J., and Morrison, H.: Midlatitude Cyclone Compositing to Constrain Climate Model Behavior Using Satellite Observations, Journal of Climate, 21, 5887-5903, doi:10.1175/2008JCLI2235.1, 2008.
Field, P. R., Bodas-Salcedo, A., and Brooks, M. E.: Using model analysis and satellite data to assess cloud and precipitation in midlatitude cyclones, Quarterly Journal of the Royal Meteorological Society, 137, 1501-1515, 10.1002/qj.858, 2011.
Manaster, A., O'Dell, C. W., and Elsaesser, G.: Evaluation of Cloud Liquid Water Path Trends Using a Multidecadal Record of Passive Microwave Observations, Journal of Climate, 30, 5871-5884, 10.1175/jcli-d-16-0399.1, 2017.
McCoy, D. T., Field, P. R., Schmidt, A., Grosvenor, D. P., Bender, F. A. M., Shipway, B. J., Hill, A. A., Wilkinson, J. M., and Elsaesser, G. S.: Aerosol midlatitude cyclone indirect effects in observations and high-resolution simulations, Atmospheric Chemistry and Physics, 18, 5821-5846, 10.5194/acp-18-5821-2018, 2018.
Qu, X., Hall, A., Klein, S. A., DeAngelis, and Anthony, M.: Positive tropical marine low-cloud cover feedback inferred from cloud-controlling factors, Geophys. Res. Lett., n/a-n/a, 10.1002/2015GL065627, 2015.

R2:

The authors are addressing the previously identified negative cloud feedback in the extra tropics, related to cloud optical depth (via LWP), and suggesting a mechanism in complement or in place of phase changes as responsible for this feedback. This is a valuable contribution.
Comparing a range of model resolutions is a useful approach (although more could be squeezed out of this comparison), as is the cyclone compositing framework.
The way the paper is written, it is somewhat difficult to distill out the main points – a multitude of figures and side tracks make the reasoning hard to follow at times. I would advise the authors to tighten up the writing, and consider reducing the number of figures presented, without simply moving them to the supplementary material. Several of the supplementary figures already play more than a supplementary role, the way the analysis is presently presented.

We thank the reviewer for their thorough appraisal of our paper and supportive feedback. In the process of writing the paper we got slightly carried away with the exciting new range of high-resolution simulations and observational data sets available. We have worked to streamline the paper and make it punchier and to make the central points of the analysis clearer. We have also restructured the sections so that our line of argument becomes clearer and refocused our analysis on the SH.

Specific comments 1. The study is based on multiple linear regression (introduced as a statement on p 4, line 22). The authors need to explain why, if at all, this is a suitable *approach. It is clear that some of the processes investigated have non-linear elements (e.g. Fig 3). It is also clear that in several cases the predictors are not independent (e.g. Eq. 4, Eq. 6). SST determines WVP through Clausius- Clapeyron, and WVP in turn is part of the definition of WCB, and hence SST and WCB, or "thermodynamics" and "meteorology" (p. 18, line 18-19), can't be separated in this way.*

As discussed in the response to R1, we used the AMIP+4K simulations to justify the use of predictions based on linear-regression in the current climate. This is following previous literature supporting inference of cloud feedbacks from the observational record with model simulations(Qu et al., 2015). However, this was not sufficiently clearly presented in the original paper and we have tried to clarify this. The reviewer makes a good point that the statement on page 4 is misleading. We have altered it to clarify that regression analysis is only part of our analysis.

The reviewer's point that WCB moisture flux is going to contain a significant thermodynamic component (eg through Clausius-Clapeyron) is very true and this discussion has been changed to reflect this throughout the paper. We have also added additional discussion of SST as a predictor of LWP and analysis showing that SST and LWP are poorly correlated.

On p.19 line 3-5 we also examined the linear regression on only one predictor at a time (importantly the dependence on SST flips, which is not consistent with simply sharing covariability and both predictors being equally good). We have added new analysis showing the generally poor correspondence between SST and LWP (Fig. 6 of the new MS and Fig. S7).

We believe that we have pushed the regression analysis in the current climate as far as we really can and that there is not evidence that covariability between WVP and SST degrades WCB moisture flux as a predictor. Further, we find that this regression model does a good job at predicting the majority of the transient climate response in models.

The authors occasionally point at these problems, but further explanation and/or justification would be needed (e.g. p. 14 line 21-24, p. 19, line 3-5). For instance, would it be possible to attempt to estimate parameters for a non-linear relation, rather than forcing a linear fit between LWP and WCB? And would it be an option to use only one predictor rather than two, when they are not independent, as is the case for WCB and SST?

In figures S7 and S8 of the previous version of the paper we utilized a non-linear regression model on WCB alone to look at predicted changes in LWP. Overall this does not produce a substantially different prediction of the change in LWP to the simple linear model. We have added an additional calculation contrasting a linear fit to WCB and find that it does not alter the prediction of WCB-driven changes in LWP (Fig. 6 of the new MS). We have also added a calculation based on SST alone (also Fig. 6).

2. It also needs to be acknowledged that the degrees of explanation are in general rather low. E.g. p 14, line 31, Fig. 5. P 1 line 33, states that WCB "can explain" trend in LWP over two decades, which is a pretty strong statement. P 4 line 13 refers to a *"clear criterion" between "synoptic state" (WCB) and LWP to test models against. I find this to be a bit optimistic, based on the results presented. On p 13, line 31-33, it also seems as if the large uncertainty in the observationally based estimate would limit the usefulness of the suggested constraint on models*

Figure 6 shows slopes of relations that (according to Fig. S5) have correlations R2 ranging from below 0.3 to above 0.7. Even though the slopes are all significantly greater than zero, the relations are in some cases rather weak, and a chain of weak correlations is simply not enough to support the conclusions drawn. Could a threshold R2 be used to select a subset of slopes to use?

'Can explain' might have been somewhat vague. The 95% confidence on the climate trend in the zonal mean from Manaster et al. (2017) is shown in Fig. 7b. We show the 95% confidence trend in cyclone LWP, and the 95% confidence trend predicted by WCB alone. These trends are all significant at this confidence interval and the interval is small. We have added some additional clarification on this statement to clarify what we mean in this case.

In regards to testing models against the observations, we show the 95% confidence on the WCB-LWP relationship in fig 6a. The range of WCB-LWP relationships that are within the observational range is quite small, and several of the models considered here fall significantly outside of it. In an objective observational sense this is our definition of a clear criterion. It is true that the R^2 values within the observations are 30-40%. Focusing on this is somewhat misleading. What we are most interested in in this case is the confidence interval on the trend. We have also added discussion of why the explained variance is low- for example, we neglected cloud droplet number concentration as a predictor, which had been shown in McCoy et al. (2018) to significantly increase explained variance. However, if CDNC stays approximately constant during the observational period, or over a transient warming (as it does in the AMIP-AMIP+4K), then this explained variance is unimportant to our ability to understand the climate response. The reviewer makes a very good point that our discussion is not sufficiently clear in regards to what our expectations are for the regression model and we have added some text to clarify this. We have also updated Fig. 2 of the new version of the paper to better show the confidence on the slope of the regression.

Another example is p 16, where the reasoning seems to be that latitude explains wind speed which explains WCB which explains precipitation. As stated by the authors, the relation between latitude and windspeed is not causal, but can be explained by poleward travelling and intensification of cyclones during their life cycle. The link to a poleward shift in storm track position is not clear. The change in latitude could leave the initial wind speed unaffected, i.e. the intensification of storms seen is not necessarily an effect of their shift in position.

As shown in Fig. S12 of the original MS the poleward shift within models predicts 86% of the change in wind speed. We do not focus on this relationship within the paper because we are not confident in explaining the causal link, but it does appear to be a robust feature of the warmed climate response and the climatological variability. We have moved Fig. S12 to the main text to clarify this argument. We have added additional text explaining that the shift in mean storm position is likely to indicate some basic change in the cyclone lifecycle in response to warming and that we are reserving trying to better understand this linkage for a future paper.

The weak relations also cause problems in the attempts to compare present climate to future (warmer) conditions. On p 20 it remains unexplained why shifts in the LWP-WCB relation occur and why in the NH (Fig. s9) the shift changes sign between low and high WCB, but it is clear that the assumption that the relationship between WCB and LWP is invariant under warming (p 20 line 4) does in fact not hold, other than within a large range of uncertainty.

As shown in Fig S10 and S11 the majority of the LWP change between AMIP and AMIP+4K simulations can be calculated based on the current climate's WCB-LWP relationship and the WCB moisture flux change between AMIP and AMIP+4K. The assumption is that this shift may be related to any other changes in the clouds with warming (for example a phase transition). We have added some text to clarify that we are not assuming that the relationship holds. We are testing how much the relationship can predict. To clarify this we have added these sentences:

"This analysis tests the assumption that the relationship between WCB moisture flux and LWP is invariant under warming."

3. The paper claims to show that precipitation is balanced by WCB, but I would argue that this is not shown, but rather assumed in Section 3.1., and then used to motivate the continued analysis.
*Eq. 3 relates WCB to WVP and WS as WCB=k*WVP*WS. Line 10, however, states that the constant of proportionality k is defined based on regression of precipitation rate on WVP and WS, i.e. precipitation=k*WVP*WS. This suggests that an equivalence between WCB and precipitation rate is assumed. This is a logical problem (assuming a relation you set out to test) and a physical problem (as there may be a fraction of the precipitation that is not related to the WCB , see e.g. Pfahl et al. 2013, https://journals.ametsoc.org/doi/10.1175/JCLI-D-13-00223.1)*
*Further down, a "match" between moisture flux into and precipitation out of a cyclone is said to be examined (page 11, line 14-16), and Fig. 2 suggests that models' estimate of the relation between precipitation and WVP*WS is in general agreement with observations (with large uncertainty). It needs to be sorted out what is assumed and what is investigated, in observations and models, and the recurring assumption that WCB can be replaced with precipitation needs explanation and/or justification.*
*With the current presentation, the statement on P12 Line 16 is not correct; section 3.1 doesn't show that precipitation is predicted by WCB, it shows that WS*WVP is well correlated with (or "predicts") WCB, and it is assumed that WCB is perfectly balanced by precipitation.*
On p 13, line 5 it is contrarily stated that the relation that has so far been assumed between WCP and precipitation can't be evaluated. Adding LWP to the discussion here (p 12-13) does not necessarily help. A time aspect seems to be missing, as it is assumed that more moisture flux in is balanced by more precipitation, but in between an observable build-up of liquid water is expected. This requires some explanation. One option would be to exclude the section on precipitation, and focus the paper on

the discussion of the role of WCB in determining LWP.

The reviewer is correct that this was presented as being shown and it should have been presented as being a predictor-predictand relationship. Overall, our results are insensitive to this. The paper has been updated to reflect that we find that WCB moisture flux is generally in good agreement with precipitation out of the cyclone, but we cannot show that it is balanced by it.

4. Some other methodological choices are also not clear or explained, e.g. the separation between NH and SH in some cases, and in others not. Please make clear when and why this separation is useful or meaningful. The main focus seems to be on the SH and the Southern Ocean, and perhaps it could be motivated to make that focus even more distinct.

The reviewer makes a good point that the analysis was somewhat unfocused. We have refocused the manuscript to examine the SH. The SH is of particular interest because of the large model-predicted negative cloud feedback in this region and the observed trends(Manaster et al., 2017). However, we want to note that the relationships we find in the SH are for the most part replicated in the NH and this material has been moved to the SM in case readers want to satisfy themselves that this is not a phenomena that is specific to the SH. The exception to only showing the SH in the new MS is the analysis of AIRS cloud top phase. AIRS detects a very large amount of unknown-topped cloud in the SH. We discuss why this is likely to happen and possible changes to the retrieval algorithm that might improve this. However, to be able to say something useful about how LWP changes and phase changes might be related in extratropical cyclones we found it useful to include NH and SH observations. We have added this text to explain why we are doing this:

“In this work we have focused on the SH for brevity because it is interesting from a modelling perspective and because the behavior of cyclone LWP as a function of WCB moisture flux in the NH is approximately the same, giving little additional explanatory value to including it. However, the preponderance of unknown-topped cloud observed by AIRS in the SH necessitates contrasting NH and SH midlatitude oceans to offer insight into whether cloud top phase changes might explain some of the response of LWP to SST within cyclones.“

5. P13, line 8-10 The statement has been reversed, according to Fig. S2 the ratio LWP/TLWP decreases with increasing WCB. This is problematic as it contrasts with the following statement that LWP increases with increasing WCB in general. This does not follow from Fig S2. In Fig .3 the relation between LWP and WCB has the expected sign. On p 14, lines 1-2 a more reasonable interpretation of Fig s2 and fig 3 is made: at higher WCB the partitioning of LWP is more biased towards rain, and this contributes to the asymptotic shape of the LWP-curve in fig 3. I would encourage the suggested future study of this aspect.

Thank you, this was typo in this sentence. We have shifted the material on p14 line 1-2 to explain this here instead of ending with this statement in the section.

We also think this is a very interesting feature and are working toward evaluating it in a perturbed parameter ensemble in the UM. Thank you for clarifying this statement.

6. P16, lines 1-5 (Fig. S3) indicates that a shift of 5 degrees improves the correlation *between LWP and WCB. P 18 uses a new choice of latitude range, to agree with Manaster et al. (2107) How region-sensitive might the analysis be, or rather what is the motivation for the chosen regions?*

The region choice of 30-80° was based on the compositing technique used in Field and Wood (2007). However, we suspect that cyclones near 30° are undergoing the tropical-extratropical transition and the moisture flux-LWP mechanism that we propose is less relevant to these cyclones. To support this statement we showed the maps with a 5° shift. We felt it would be disingenuous to select a latitude region that gave a higher explained variance so we stuck with 30-80°. Overall, the WCB-LWP relationship's slope does not change so our proposed climate feedback is not sensitive to this choice- even if the inclusion of transitioning cyclones adds some noise to the relationship. In order to compare to Manaster et al. (2017) we had to select a similar latitude range to look at the decadal trend. We have removed this aside because it doesn't add much and distracts from the flow of the paper.

The following sentence has been added to the methods to explain our choice of 30-80° "For consistency with previous studies utilizing the Field and Wood (2007) cyclone compositing algorithm cyclone centers must have their center between 30° and 80° latitude."

7. It is not clear how the regression of albedo on LWP accounts for cloud masking. (Page 22, line 12 and onward, particularly lines 22 -33 of page 22) It seems like the exercise described here is an attempt to quantify the albedo changes due to changes in LWP due to changes in WCB (or SST), i.e. the suggested feedback mechanism, not to correct for overlying ice clouds. The summarizing sentence on p 23, line 6 also indicates that this is what has been done, rather than accounting for cloud masking

The logic behind this back of the envelope calculation was that the CERES albedo will include contributions to the optical depth from overlying ice cloud. If, for example, all cyclones had an infinitely thick ice-cloud over the liquid cloud then the sensitivity of top of atmosphere albedo to microwave LWP would be zero (the LWP could do whatever it liked beneath the ice cloud). As the reviewer says, the goal of this exercise is to quantify the change in albedo consistent with a change in LWP driven by a change in WCB or SST. However, to do that we need to account for overlying ice cloud somehow, otherwise our feedback would be unrealistically large. We have added some additional text to try and clarify this:

"In particular, overlying cloud can act to blunt the effect of changes in LWP on top of atmosphere reflected shortwave radiation. For example, an optically thick layer of ice cloud over the liquid in the cyclone would result in very little impact from LWP variability. We offer an approximate calculation of the change in reflected shortwave radition consistent with the coefficients calculated in Eq. 6 using observations from CERES. The idea underlying this calculation is that the CERES top of atmosphere reflected shortwave radiation will include the effects of overlying ice cloud. The sensitivity in reflected shortwave radiation to LWP will be lowered by the effects of ice cloud."

Technical comments Fig1: Observations should be MERRA reanalysis

Changed

P3, line 10 "increases or decreases"

Changed

P3 line 14 "optical depth increase" should rather read "optical depth change" as it was just stated that it is unclear if it is an increase or a decrease

Changed

P3, line 22, line 24 "reflected shortwave" should be followed by radiation

Changed

In section 2.1 I would suggest to present the Cyclone compositing (2.1.2) before the Regression analysis (2.1.1), as the compositing is referred to in 2.1.1. but not explained until 2.1.2.

Thank you- that is clearer.

Section 2.1.2 Cyclone compositing , p5, could use some clarification. E.g. line 9 "before and after" what? please clarify if p_0' is a function of time or of x,y only. Line 9 "Candidate gridpoints" means what? Line 14 "maximum negative anomaly within 2000 km" of what? Line 17 "of the figure", comes without previous reference to a figure

Clarification has been added. We tried to shorten this section as it reproduces the original text in Field and Wood (2007).

Page 5, line 28 Please clarify what "bias-corrected" refers to. The following paragraphs describes various identified problems with the MAC LWP data, but it is not clear which if any of these are corrected for, or if excluding certain years and judging surface contamination as irrelevant is the bias correction

Thank you- this needed to be clarified. We have added the following:

"Bias correction was performed using observations from Aqua MODIS. As a function of WVP and 10-m surface wind, Aqua MODIS was used to determine clear-sky (here, by definition, LWP = 0) scenes, and these scenes were compared to AMSR-E LWP. If a non-zero difference was computed between AMSR-E and MODIS LWP, this difference was removed from all individual input LWP records (as a function of WVP/wind) prior to processing in the MAC algorithm. This LWP bias correction is discussed in more detail in Elsaesser et al. (2017)."

P6, line 26 please spell out FOV. Throughout, there are many abbreviations, some of which may not be necessary to introduce.

Changed

P7 line 25 Please explain Easy Aerosol. As the abbreviations mentioned above, jargon makes the paper more difficult to follow.

Thank you, a citation to the relevant paper has been added.

P7 line 29 How are these "three resolutions" of HadGEM3 referred to?

We have added a note that they are referred to as LM, MM, and HM.

P8, line 30 "in more detail"

Changed

P10, line 8-9 This statement raises more questions than it answers. I would suggest to

explain, or remove it
Removed- it is irrelevant in this case.

P10, line 23 The statement "The January SST was reflected north-south" needs explanation
This has been expanded for clarity.

Page 12, line 8: the word models seems to be missing, midlatitude-cyclones can hardly be said to under-estimate precipitation
Very true- thank you.

Page 12 line 10-12 Look over this sentence, it does not make sense
Thank you- there was a typo.

P 13, line 9 fix typo "...results in a decreases the..."
Thank you- fixed

P14 line 31 missing "is"
Fixed

P14, line 13 "poleward of 30-80N" should be "between 30 and 80N"
Fixed

P 14 line 25 one "of" too many
Fixed

P21, line 15-17 please look over this sentence, perhaps removing "that" is all that is Needed
Fixed

P22 line 15 "shortwave radiation"
Fixed

P22 line 18 "these data"
Fixed

P24, line 8 "the magnitude"
Fixed
P24 line 24-26, please look over this sentence
This has been removed to shorten the paper.
The paper has a somewhat abrupt ending, please consider a final sentence to wrap up. This would be made easier if the whole paper could be more condensed.
We have tried to rewrite the paper for clarity. Thank you for your advice.

We have changed the conclusion section to have a more rounded discussion and a better ending. Thank you again for your insight.

Cloud feedbacks in extratropical cyclones: insight from long-term satellite data and high-resolution global simulations

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Abstract. ~~Extratropical cyclones provide a unique set of challenges and opportunities in understanding variability in cloudiness over the extratropics (poleward of 30°).~~ A negative extratropical shortwave cloud feedback driven by changes in cloud optical depth is a feature of global climate models (GCMs). A robust positive ~~increasing~~ trend in observed liquid water path (LWP) over the last two decades across the warming Southern Ocean supports the negative shortwave cloud feedback predicted by GCMs. This feature has been proposed to be due to transitions from ice to liquid with warming. ~~We can~~To gain insight into the shortwave cloud feedback ~~from~~ we ~~examining~~ examine extratropical cyclone variability and the response of extratropical cyclones to transient warming in GCM simulations. ~~Here we contrast global climate models (GCMs) with horizontal resolutions from 7 km up to hundreds of kilometers with~~ Multi-Sensor Advanced Climatology Liquid Water Path (MAC-LWP) microwave observations of cyclone properties from the period 1992-2015 are contrasted with GCM simulations with horizontal resolutions ranging from 7km to hundreds of kilometers. We find that inter-cyclone variability in LWP in both observations and models is strongly driven by moisture flux along the cyclone's warm conveyor belt (WCB). Stronger WCB moisture flux enhances the ~~liquid water path (~~LWP~~)~~ within cyclones. This relationship is replicated in GCMs, although its strength varies substantially across models. It is found that more than 80% of the enhancement in SH extratropical cyclone LWP in GCMs in response to a transient 4K warming can be predicted based on the relationship between WCB moisture flux and cyclone LWP in the historical climate and their change in moisture flux between the historical and warmed climates. Further, it is found that the majority of the robust trend in cyclone LWP over the Southern Ocean in observations and GCMs can also be predicted by changes in moisture flux. ~~In the southern hemisphere (SH) oceans 28-42% of the observed interannual~~

~~variability in cyclone LWP may be explained by WCB moisture flux variability. This relationship is used to~~We propose two cloud feedbacks acting within extratropical cyclones: a negative feedback driven by Clausius-Clapeyron increasing water vapor path (WVP), which enhances the amount of water vapor available to be fluxed into the cyclone; and a feedback moderated by changes in the life cycle and vorticity of cyclones under warming, which changes the rate at which existing moisture is imported into the cyclone. Both terms contribute to increasing LWP within the cyclone. -While changes in moisture flux predict cyclone LWP trends in the current climate and the majority of changes in LWP in transient warming simulations, a portion of the LWP increase in response to climate change that is unexplained by increasing moisture fluxes may be due to phase transitions. ~~We show that changes in moisture flux drive can explain the observed trend in Southern Ocean cyclone LWP over the last two decades. Transient warming simulations show that the majority of the change in cyclone LWP can be explained by changes in WCB moisture flux, as opposed to changes in cloud phase.~~ The variability in LWP within cyclone composites is examined to understand what cyclonic regimes the mixed phase cloud feedback is relevant to. At a fixed WCB moisture flux cyclone LWP increases with increasing SST in the half of the composite poleward of the low and decreases in the half equatorward of the low in both GCMs and observations. Cloud-top phase partitioning observed by the Atmospheric Infrared Sounder (AIRS) indicates that phase transitions may be driving increases in LWP in the poleward half of cyclones.

1 Introduction

Constraining the ~~brightening or dimming of clouds~~change in cloud reflectivity in response to warming is key to offering a more accurate prediction of 21st century climate change. Caldwell et al. (2016) showed that uncertainty in shortwave cloud feedback represented the largest contribution to uncertainty in climate sensitivity in the fifth ~~climate~~ coupled model intercomparison project (CMIP5) generation of models. Model uncertainty in the shortwave cloud feedback is driven by differences in the representation of clouds in the planetary boundary layer, which contribute strongly to albedo, but not to outgoing longwave radiation (Hartmann and Short, 1980). These clouds exist at a time- and length-scale that is much finer than even the highest resolution simulation and are thus parameterized, leading to substantial disagreement in feedback from one model to another.

The shortwave cloud feedback, while highly variable across models, does have some qualitatively similar features that appear in many CMIP-class GCMs. The most salient of these is the dipole pattern in the shortwave cloud feedback (Zelinka et al., 2012b, a;Zelinka et al., 2013;Zelinka et al., 2016). The shortwave cloud feedback dipole is characterized by decreasing cloud coverage in the subtropics (a positive feedback) and increasing cloud optical depth in the extratropics (a negative feedback) in response to warming. There is a growing consensus that the positive lobe of the dipole, where subtropical cloud fraction decreases, is a robust feature of the climate system. Both empirical analysis of observations (McCoy et al., 2017a;Clement et al., 2009;Klein et al., 1995;Myers and Norris, 2015, 2016;Norris et al., 2016) and very high resolution simulations (Blossey et al., 2013;Bretherton, 2015;Bretherton and Blossey, 2014;Bretherton et al., 2013;Rieck et al., 2012) have substantiated the subtropical positive feedback predicted by GCMs, although it appears that traditional GCMs somewhat underpredict the decrease in subtropical cloud cover in response to warming and thus underestimate the positive feedback (Klein et al., 2017).

With the growing consensus surrounding the positive lobe of the dipole, a constraint on the negative lobe, where extratropical cloud optical depth increases with warming, has increased in importance as a significant source of uncertainty in the global-mean shortwave cloud feedback. Evaluation of model behavior and some observations indicate that the negative lobe is related to a transition from a more ice-dominated to a more liquid-dominated state – the so called *mixed phase cloud feedback* (McCoy et al., 2017b;Ceppi et al., 2016a;Tsushima et al., 2006;Cheng et al., 2012;Naud et al., 2006;Choi et al., 2014). This transition results in an increase in small, bright liquid droplets at the expense of ice crystals and thus an increase in albedo(Zelinka et al., 2012a;McCoy et al., 2014). It is possible that this transition also decreases precipitation efficiency by decreasing the amount of frozen hydrometeors (Field and Heymsfield, 2015;Morrison et al., 2011;Heymsfield et al., 2009), and enhancing the total condensate.

GCMs struggle to realistically simulate mixed-phase clouds. Evaluation of ice-liquid partitioning in GCMs participating in CMIP5 showed that there was a 30 K temperature range in which different models predicted an equal mixture of ice and liquid within clouds(McCoy et al., 2016). This model diversity in partitioning leads to a diversity in LWP response to warming and ultimately shortwave cloud feedback in the extratropics(Tan et al., 2016). Models that glaciate at a warmer temperature transition more ice to liquid with warming, simply because they have a large reservoir of susceptible cloud ice in the climate mean state(McCoy et al., 2015b).

The mixed-phase cloud transition mechanism is partially supported by the observationally-inferred response of extratropical clouds to warming. Several studies have substantiated that cloud optical depth responds to atmospheric and surface temperature in the midlatitudes, particularly the Southern Ocean (SO)(Ceppi et al., 2016b;Terai et al., 2016;Gordon and Klein, 2014). Multiple linear regression of cloud optical depth on atmospheric stability and temperature shows that increasing surface temperature tends to decrease cloud optical depth ~~, although there is not a strong consensus as to whether cloud optical depth increases or decrease with increasing SST when changes in atmospheric stability are considered~~(Terai et al., 2016). These investigations examined the variability across the midlatitudes in a non-phenominological sense, making it difficult to assign a mechanism to their diagnosed covariability between optical depth, LWP, and temperature. Overall, it remains unclear if this optical depth ~~increase~~ change is directly related to shifts in cloud phase because it is difficult to accurately measure the phase of water in clouds and the total amount of frozen water (Jiang et al., 2012). In addition to the difficulties in measuring ice-phase cloud properties, the diversity in synoptic states in the midlatitudes further complicates this analysis. Bodas-Salcedo (2018) demonstrated that the radiative signal from increased LWP associated with phase transitions is masked by ice cloud within low pressure systems. This shows that extratropical variability in LWP needs to be considered in the context of the regime it is occurring in. This is supported by earlier studies that demonstrated that there was strong regime dependence in the bias in reflected shortwave radiation across SH extratropical cyclones (Bodas-Salcedo et al., 2014). Shifts in cyclonic regimes have been suggested as a possible explanation for negative midlatitude shortwave cloud feedback. Tselioudis and Rossow (2006) proposed that changes in cyclone frequency and ~~surface pressure depression~~surface pressure in response to a doubling in CO_2 could increase reflected shortwave radiation over the midlatitudes by ~~between~~ 1.9 Wm^{-2} ~~and~~ to

4.9 Wm^{-2} ~~due to changes in intensity and frequency of cyclones in a warmed climate and the observed relationship between these properties and reflected shortwave in the current climate~~. Despite the complexity of midlatitude feedback processes, robust ~~decadal~~ increases in extratropical cloud cover (Norris et al., 2016) and liquid water path (Manaster et al., 2017) have been observed over the 25 years covered by satellite observations. It is reasonable to hypothesize that warming in the extratropics might be driving these trends partly via changes in cloud phase from ice to liquid. Can our understanding of the large synoptic systems that dominate the extratropics assist us in interpreting the long-term cloud property trends observed across these regions?

In this study we follow a similar technique to Tselioudis and Rossow (2006) and examine observations of midlatitude cyclones to infer a feedback. However, this is difficult to interpret in a causal sense. GCMs are used to support inferences made by examining observed covariability in the current climate. The cloud organization within midlatitude cyclone systems exists on a variety of length scales from synoptic (thousands of kilometers) to mesoscale cellular convection (kilometers). Traditional GCMs are able to capture the overall synoptic length scale, but are typically too coarse to capture the finer structures. Here, we utilize a diverse selection of GCMs with resolutions as fine as 7km to examine the impact of resolving these features. From these simulations we hope to ~~not only support the existence of the mechanisms we propose based on observations, but to~~ offer guidance as to what aspects of models are important to capturing midlatitude variability and cloud feedback.

~~In summary, we~~We will show that the mixed-phase cloud feedback does not explain all of the observed variability or trends in extratropical LWP within cyclones in both observations and GCMs by showing that changes in moisture flux into the cyclones predict the majority of the change in LWP in response to warming. This is done by sorting our observations and simulations into cyclonic regimes across the extratropics. We show how clouds in cyclones have their LWP variability explained by meteorological variability and that trends in meteorological variability ~~explain~~ predict the majority of decadal trends in cyclone LWP. Similarly, changes in cyclone LWP between simulations forced with observed SST and simulations with enhanced SST can be explained by changes in moisture flux into cyclones. This work builds on earlier insight by Kodama et al. (2014) who utilized aquaplanet simulations to posit that a relationship between SST and WVP modulated by Clausius-Clapeyron within extratropical cyclones should lead to a negative cloud feedback, in keeping with Betts and Harshvardhan (1987). We hope that the relationships between synoptic state and cyclone cloud LWP in this work provides a clear ~~criterion~~ benchmark that models may be evaluated against and will reduce uncertainty related to the extratropical shortwave cloud feedback in models.

2 Methods

In this section we discuss the methodology used to identify the low-pressure centers of midlatitude cyclones. We compare microwave observations of cyclone properties to global model simulations ranging from CMIP5 GCMs with horizontal resolution in excess of 100 km, to convection-permitting GCMs with a resolution of approximately 7 km. The methodology used to create the unified microwave observations, cloud top phase, and the model set up for the global simulations is described in this section as well.

2.1 Data analysis

2.1.12 Cyclone compositing

Numerous studies have examined midlatitude variability by compositing around cyclone centers (Field et al., 2011;Field and Wood, 2007;Naud et al., 2016;Catto, 2016;Naud et al., 2017;Grandey et al., 2013). Identification of cyclone centers may be achieved by using pressure (Jung et al., 2006;Löptien et al., 2008;Hoskins and Hodges, 2002;Field et al., 2008); geopotential height (Blender and Schubert, 2000); or vorticity (Sinclair, 1994;Hoskins and Hodges, 2002;Catto et al., 2010). Here we follow the methodology described in Field and Wood (2007). As in Field and Wood (2007) SLP is averaged to 2.5° resolution. Daily-mean aAnomalies in SLP (p_0') are calculated by subtracting the average of SLP starting from 15 days before andto 15 days after atfrom each pointday for each 2.5°x2.5° region. -Candidate 2.5°x2.5° grid points were found using the following criterion:

$$\frac{dp_0'}{dx}\frac{dp_0'}{dy} < 3 \cdot 10^{-5} hPa\ km^{-2} \qquad [1]$$

and

$$\frac{d^2p_0'}{dx^2} + \frac{d^2p_0'}{dy^2} > 6 \cdot 10^{-5} hPa\ km^{-2} \qquad [2]$$

where SLP<1015 hPa. As in Field and Wood (2007) SLP is averaged to 2.5° resolution, and each composite is 4000 km across.. These candidate 2.5°x2.5° grid points are filtered to find the maximum negative anomaly within a 2000km radius of each grid point. Each composite is 4000 km across. Composited data is averaged onto an equal-area grid centered around the maximum negative anomaly. The averaging grid was 18 zonal bins by 19 meridional bins. In this study we examine NH and SH cyclones. . For consistency with previous studies utilizing the Field and Wood (2007) cyclone compositing algorithm cCyclone centers must behave their center between 30° and 80° latitude. SH cyclones are flipped in the north-south direction so that all cyclones are oriented with the pole to the top of the figure. This is done to allow easy comparison of cyclone composites in the NH and SH. All cyclone means are the average of all data within 2000 km of the cyclone center. More complex analysis techniques exist that allow the definition of the edge of a cyclonic system(Pfahl and Sprenger, 2016). We have chosen to take averages around low pressure centers of with a set radius.

Some microwave radiometer products are unavailable over land or ice (e.g., surface wind), while others have larger uncertainty resulting from atmospheric emission signals being occasionally overwhelmed by land or ice emission (e.g., cloud liquid water). Therefore, only cyclone centers with 50% or more of the composite area located over ice-free ocean are considered valid in cyclone composites from observations or models. Model data over sea ice or land are removed from the composite to ensure parity with the observations. The number of cyclone centers identified for each GCM and the observations are shown in .

2.1.21 Regression analysis

In this work we examine observed and simulated extratropical variability in the current climate in the context of linear regressions. This framework is used to infer a climate feedback from changes in cyclone properties and these inferred feedbacks are tested in a set of simulations of transient warming following Qu et al. (2015).

In the cyclone compositing framework that this paper is built on we examine (i) variability of different variables between cyclones within the coordinate system of the cyclone composite (e.g. the inter-cyclone variability in some region of the composite), (ii) variability in mean cyclone properties across many cyclones, and (iii) seasonal and regional mean variability in cyclone means (e.g. the average cyclone LWP for all cyclones in a given region). To add clarity to our analysis we will refer to a given cyclone property X as X_{CM} when a cyclone-wide mean is taken (where the mean of all data is within a 2000 km radius of the low pressure center) and X_{RM} when we are examining the regional mean of many different cyclones. (Pfahl and Sprenger, 2016)(Bodas-Salcedo et al., 2016a;Bodas-Salcedo et al., 2016b;Bodas-Salcedo et al., 2012;Bodas-Salcedo et al., 2014;Field et al., 2011) In the case where we will investigate the spatial variability around the low-pressure center we will write X_{ij} to signify the different averaging regions within the composite. In the case of some variables only cyclone-means are defined (e.g. WCB moisture flux into the cyclone) and the 'CM' subscript is not written. A list of acronyms and subscripts is given in Table 1Table 1.

2.1.2 Cyclone compositing

Numerous studies have examined midlatitude variability by compositing around cyclone centers (Field et al., 2011;Field and Wood, 2007;Naud et al., 2016;Catto, 2016;Naud et al., 2017;Grandey et al., 2013). Identification of cyclone centers may be achieved by using pressure (Jung et al., 2006;Löptien et al., 2008;Hoskins and Hodges, 2002;Field et al., 2008); geopotential height (Blender and Schubert, 2000); or vorticity (Sinclair, 1994;Hoskins and Hodges, 2002;Catto et al., 2010). Here we follow the methodology described in Field and Wood (2007). Anomalies in SLP (p'_0) are calculated by subtracting the average of SLP from 15 days before and after at each point. Candidate grid points were found using the following criterion:

$$\frac{dp'_0}{dx}\frac{dp'_0}{dy} < 3 \cdot 10^{-5} hPa\ km^{-2} \qquad [1]$$

and

$$\frac{d^2p'_0}{dx^2} + \frac{d^2p'_0}{dy^2} > 6 \cdot 10^{-5} hPa\ km^{-2} \qquad [2]$$

where SLP<1015 hPa. As in Field and Wood (2007) SLP is averaged to 2.5° resolution, and each composite is 4000 km across. These candidate grid points are filtered to find the maximum negative anomaly within 2000km. Composited data is averaged onto an equal-area grid. The averaging grid was 18 zonal bins by 19 meridional bins. In this study we examine NH and SH cyclones. Cyclone centers must be between 30° and 80° latitude. SH cyclones are flipped in the

~~north-south direction so that all cyclones are oriented with the pole to the top of the figure. This is done to allow easy comparison of cyclone composites in the NH and SH.~~

~~Some microwave radiometer products are unavailable over land or ice (e.g., surface wind), while others have larger uncertainty resulting from atmospheric emission signals being occasionally overwhelmed by land or ice emission (e.g., cloud liquid water). Therefore, only cyclone centers with 50% or more of the composite area located over ice-free ocean are considered valid in cyclone composites from observations or models. Model data over sea ice or land are removed from the composite to ensure parity with the observations. The number of cyclone centers identified for each GCM and the observations are shown in Fig. 1.~~

2.2 Observations and reanalysis

2.2.1 MAC-LWP

The Multi-Sensor Advanced Climatology framework used for developing monthly cloud water products (Elsaesser et al., 2017) is adapted for use here to create diurnal-cycle corrected and bias-corrected daily datasets for liquid water path (LWP, where path is the mass in an atmospheric column), 10-meter wind speed, and water vapor path (WVP). Bias correction was performed using observations from Aqua MODIS. As a function of WVP and 10-m surface wind, Aqua MODIS was used to determine clear-sky (here, by definition, LWP = 0) scenes, and these scenes were compared to AMSR-E LWP. If a non-zero difference was computed between AMSR-E and MODIS LWP, this difference was removed from all individual input LWP records (as a function of WVP/wind) prior to processing in the MAC algorithm. This LWP bias correction is discussed in more detail in Elsaesser et al. (2017).

Because passive microwave cloud liquid water retrievals must make assumptions regarding the partitioning of precipitating and non-precipitating liquid there is a systematic uncertainty in the microwave LWP data set. The cyclone LWP observations from this data set that are used in this study are the estimated non-precipitating liquid water averaged over both cloudy- and clear-sky, with the bias (largely due to the aforementioned precipitation partitioning errors) estimated to be ~0.01-0.02 kg m^{-2} for the mid-latitude regions analyzed here (Greenwald et al., 2018).

MAC-LWP uses data from multiple microwave radiometers to create a data set spanning 1988-2016. However, up until 1991 the only data source was F08 SSM/I, which therefore implies greater uncertainty in daily averages prior to 1992 (since only two satellite overpasses per day would go into such estimates). Thus, we consider this period less reliable and only obervations onwards from 1992 are considered in this study. Because sea surface temperature and sea ice coverage are only available through 2015 we do not examine extratropical cyclones after this period.

One possible caveat in our analysis is that the radiative signal used to retrieve LWP may partly arise from upwelling radiation due to wind roughening of the ocean surface or emission from WVP. In such cases, LWP is biased in one direction, while wind and/or WVP may be biased in an opposite direction (Elsaesser et al., 2017). However, retrievals of WVP and wind speed have been shown to be unbiased relative to in situ observations and thus such issues are likely minimal (Mears et al., 2001;Wentz, 2015;Trenberth et al., 2005;Meissner et al., 2001;Elsaesser et al., 2017).

2.2.2 MERRA2

The Modern-Era Retrospective Analysis for Research and Applications version 2(Bosilovich et al., 2015) (MERRA2) daily-mean sea level pressure (SLP) was used to locate cyclone centers in the observational record from 1992-2015 using the algorithm described above.

2.2.3 AIRS Cloud-top phase partitioning

The Atmospheric Infrared Sounder (AIRS) instrument on NASA's EOS Aqua satellite provides estimates of cloud thermodynamic phase (liquid, ice, and unknown categories) (Kahn et al., 2014). The cloud phase algorithm is based on a channel selection that exploits differences in the index of refraction for liquid and ice (Nasiri and Kahn, 2008), while more ambiguous spectral signatures are classified as unknown phase. Jin and Nasiri (2014) showed that ice cloud within the AIRS ~~FOV~~ field of view is correctly identified in excess of 90% of the time when compared to estimates of thermodynamic phase from Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO; Hu et al. (2010)). Liquid phase clouds dominate subtropical stratocumulus regimes (Kahn et al., 2017) while unknown phase clouds are found most frequently in trade cumulus regimes and the cold sector of extratropical cyclones (Naud and Kahn, 2015). Observations from the ascending and descending orbits of AIRS were averaged together to approximate a daily mean.

2.2.4 SST and sea ice

The Met Office Hadley Centre sea ice and sea surface temperature data set (HadISST.2.1.0.0, Titchner and Rayner (2014)) was used to provide sea ice coverage and sea surface temperature (SST) within the cyclone composite for both models and observations up until 2015. HadISST.2.1.0.0 SST and sea ice cover was also used to provide boundary conditions for the atmosphere-only PRIMAVERA simulations described below.

2.3 Simulations

In this study we have assembled a broad array of GCMs to examine their midlatitude variability. Model resolutions range from quite coarse, consistent with long integrations performed as part of CMIP5, to high resolution simulations performed under the auspices of PRIMAVERA for CMIP6, UM-CASIM, ICON, and NICAM. These simulations have long integration records and their trends may be compared to observations. Two very high-resolution simulations (nearer to 7km horizontal resolution) are also considered. Because of their demand on computational resources only short integrations are available, but they allow insight into the representation of midlatitude processes in the convective grey zone(Field et al., 2017). Simulations are described ~~below~~ in detail in the supplementary material and are listed in Table 2~~Table 2~~. Short descriptions of the CFMIP2 and PRIMAVERA model intercomparisons are provided below.

2.3.1 CFMIP2

We consider several models from the CMIP5 models participating in CFMIP2. These models are listed in Table 2~~Table 2~~. Atmosphere-only (AMIP) simulations using observed SST as a boundary condition are available for the period 1979-2008. In addition, simulations were performed with SST uniformly increased by 4K (AMIP+4K). The contrast between these sets of simulations will be used to investigate warming-induced changes in extratropical cyclones.

2.3.2 PRIMAVERA

The PRocess-based climate sIMulation: AdVances in high-resolution modelling and European climate Risk Assessment (PRIMAVERA) project is intended t~~“T~~o develop~~ a new generation of advanced and well-evaluated~~ high-resolution ~~global climate models~~GCMs~~, capable of simulating and predicting regional climate with unprecedented fidelity, for the benefit of governments, business and society in general.”~~. Several European modelling centers have coordinated to run instances of their CMIP6 models at increased horizontal resolution. These simulations use Easy Aerosol(Voigt et al., 2014) to unify aerosol perturbations across the models. At the time of writing historical simulations with prescribed SST and sea ice have been completed for the models analyzed here. These simulations allow insight into whether increasing horizontal resolution impacts the ability of models to realistically represent midlatitude variability. High resolution models are labeled HR and low resolution is labeled LR, with the exception of HadGEM3, which has three resolutions (low resolution is labeled LM, middle resolution is labeled MM, and high resolution is labeled HM). PRIMAVERA simulations are performed under the HighResMIP protocols outlined by the climate model intercomparison project panel.

~~2.3.2.1 EC-Earth~~

~~The EC-Earth model used for HighResMIP/PRIMAVERA is part of the EC-Earth3-familiy. EC-Earth 3 is a successor of the version 2.3 used for CMIP5 (Hazeleger et al., 2012). The version used in HighResMIP is EC-Earth3.2.P. Compared to version 2.3, EC-Earth3.2.P includes updated versions of its atmospheric and oceanic model components, as well as a higher horizontal and vertical resolution in the atmosphere.~~

~~The atmospheric component of EC-Earth is the Integrated Forecast System (IFS) of the European Centre for Medium Range Weather Forecasts (ECMWF). Based on cycle 36r4 of IFS, it is used at T255 and at T511 resolution for the standard and high resolution simulation in HighResMIP, respectively. It uses a reduced Gauss-grid with 91 vertical levels. The nominal resolution is about 100km x 100km in standard resolution and 50 x 50 km in high resolution.~~

~~The ocean component is the Nucleus for European Modelling of the Ocean (NEMO, (Madec, 2008)). It uses a tri-polar grid with poles over northern North America, Siberia and Antarctica with a resolution of about 1 degree (the so-called ORCA1-configuration) and 75 vertical levels (compared to 42 levels in the CMIP5 model version) in the standard resolution. In high resolution, the ORCA025 configuration is used with a resolution of about 0.25 degree.~~

~~The ocean model version is based on NEMO version 3.6 and includes the Louvain la Neuve sea-ice model version 3 (LIM3, (Vancoppenolle et al., 2012)), which is a dynamic-thermodynamic sea-ice model with five ice thickness categories.~~

The atmosphere and ocean/sea ice parts are coupled through the OASIS (Ocean, Atmosphere, Sea Ice, Soil) coupler.

The high-resolution configurations (T511 atmosphere and ORCA025 ocean, coupled or stand-alone) have been newly developed for EC-Earth 3. The high-resolution NEMO configuration is based on a set-up developed by the ShaCoNEMO collaboration and adapted to the specific atmosphere coupling used in EC-Earth. Particularly, the remapping of runoff from the atmospheric grid points to runoff areas on the ocean grid has been re-implemented to be independent of the grid resolution. This is done by introducing an auxiliary model component and relying on the interpolation routines provided by the OASIS coupler. In a similar manner, forcing data for the atmosphere is passed through a separate model component, which allows use of the same forcing data set for different EC-Earth configurations.

A full description of EC-Earth3.2.P and its ability to simulate the climate can be found in Haarsma (2018).

2.3.2.2 HadGEM3

HadGEM3-GC3.1 is described in Williams et al. (2018). The atmospheric only simulations used in this paper comprises component configurations Global Atmosphere 7.1 (GA7.1), Easy Aerosol, and JULES Global Land 7.1 (GL7.1) described in Walters et al. (2017). GA7.1 dynamical core ENDGame uses a semi-implicit semi-Lagrangian formulation to solve the non-hydrostatic, fully-compressible deep-atmosphere equations of motion (Wood et al., 2014). The microphysics used is based on Wilson and Ballard (1999), with extensive modifications described in more details in Walters et al. (2017). The parametrisation used is the prognostic cloud fraction and prognostic condensate (PC2) scheme (Wilson et al., 2008a;Wilson et al., 2008b) along with the cloud erosion parametrisation described by Morcrette (2012) and critical relative humidity parametrisation described in Van Weverberg et al. (2016). The model uses 85 vertical levels with 50 levels below 18 km and 35 levels above this, and a fixed model lid 85 km above sea level. Three different horizontal resolutions of the regular lat-lon grid are used in this study: N96, N216 and N512, which correspond respectively to a grid cell size of 135km, 60km and 25km at 50ºN, and are referred to as LM, MM and HM in the rest of the paper. The UM uses a mass flux convection scheme based on Gregory and Rowntree (1990) with various extensions to include down-draughts (Gregory and Allen, 1991) and convective momentum transport (CMT).

2.3.2.3 CNRM-CM6

The atmospheric only simulations analysed in this study are based on the atmosphere-land component of CNRM-CM6 which consists in the atmospheric model ARPEGE-Climat version 6.3, fully described in (Roehrig, 2018), and the SURFEX v8 land surface scheme(Decharme, 2018). The ARPEGE-Climat dynamical core is derived from IFS cycle 37t1. The model is operated with a T127 and a T359 truncation, the associated horizontal resolution being 120 km and 50 km for the LR and HR versions respectively. In both versions there are 91 vertical levels in the atmosphere. Compared to CNRM-CM5, the atmospheric physics has been largely revisited. In particular, convection scheme, microphysics scheme and turbulent scheme have been updated. The convection scheme (Guérémy, 2011;Piriou et al., 2007) provides a consistent, continuous, and prognostic treatment of convection from dry thermals to deep precipitating events. The microphysics scheme is derived from Lopez (2002) and takes into account autoconversion, sedimendation, ice-melting, precipitation evaporation and collection. The turbulence scheme represents the TKE with a 1.5-order scheme prognostic equation according to Cuxart et al. (2000). Surface drag over oceans is capped in CNRM-CM6 (see Soloviev et al. (2014) for general discussion). The calculations of exchange coefficients over ocean are based on an updated version of the Exchange Coefficients from Unified Multi-campaigns Estimates (Belamari, 2005) scheme.

2.3.3 NICAM

NICAM (Satoh et al., 2008;Satoh et al., 2014;Tomita and Satoh, 2004) is a non-hydrostatic atmospheric model with the icosahedral grid system. Here, climate simulation output from 14 km mesh NICAM(Kodama et al., 2015) is used for an analysis. Horizontal resolution is approximately 14 km, and 38 vertical levels are configured up to around 40 km. Instead of using convection and large-scale condensation schemes, a single moment bulk cloud microphysics scheme (Tomita, 2008) is used, in which rain, snow, and graupel as well as water vapor, cloud water, and cloud ice are treated as prognostic variables. SST is not fixed but nudged toward its monthly-mean historical distributions (Kodama et al., 2015).

2.3.4 ICON

The experiment using the ICOsahedral Non-hydrostatic (ICON) atmospheric model applied here uses a non-hydrostatic dynamical core, like NICAM, on the icosahedral grid (Zängl et al., 2015). The 1-year run was conducted as part of a development towards kilometer-scale global simulations, and as such should be considered preliminary. The grid applied here has an equivalent grid-spacing of 10 km, and in the vertical 70 levels are applied with a top around 30 km. The atmospheric physics parameterizations are from the ICON-ESM (Giorgetta et al., 2018) typically applied at much lower resolutions, but here adapted to convective cloud-permitting scales. This includes turning off all moist convective parameterizations, shallow-mid- and deep convection, as well as disabling all sub-grid scale gravity wave parameterizations and changing certain tuning parameters. These changes were to set the critical relative humidity for cloud formation everywhere to unity, setting the sub-grid scale cloud inhomogeneity factors to unity, and setting the turbulence parameterization near-neutral turbulent Prandtl number to 0.7. The input data used in this simulation was later found to contain a series of problems, however deemed irrelevant for the purposes of this study.

2.3.5 UM-CASIM

The simulations presented here are described fully in McCoy et al. (2018b) – the following description is adapted in brief below. Simulations were performed in the MetOffice Unified Model (UM) vn10.3 based on GA6 (Walters et al., 2017) in a convection-permitting setting in aquaplanet mode (no continents or sea ice). The model was run at 0.088°x0.059° and neither convection parametrization nor cloud scheme were used. Simulations lasted for 15 days and were run with 70 vertical levels. The Cloud-AeroSol Interacting Microphysics (CASIM) two-moment microphysics scheme (Hill et al., 2015;Shipway and Hill, 2012;Grosvenor et al., 2017;Miltenberger et al., 2018) was used and is described in Shipway and Hill (2012). The warm rain processes in CASIM is compared to other microphysics schemes in Hill et al. (2015). The rain autoconversion and

~~accretion rates parameterization used in CASIM are described in Khairoutdinov and Kogan (2000). Because these simulations are run in GA6 with CASIM microphysics they should not be directly compared to the HadGEM3 simulations in PRIMAVERA described above.~~

~~Sea surface temperature (SST) was held fixed in the simulations and the atmosphere was allowed to spin up for a week at low resolution and then for another week at high resolution. The SST profile used in the aquaplanet was derived from a 20-year climatology run from the UM in standard climate model configuration. The January SST was reflected north-south. The orginal and reflected SST were averaged together. The resulting SST was zonally averaged to produce a symmetrical SST.~~

~~Aerosol concentration is constant in the simulations. The aerosol profile was 100 cm^{-3} in the accumulation mode at the surface up until 5km and then exponentially decreased after 5km with an e-folding of 1 km. Aerosol-cloud interactions were parameterized using a simple Twomey-type parameterization of cloud droplet number concentration (CDNC) (Rogers and Yau, 1989) $CDNC = 0.5N_{acc}w^{0.25}$ with N_{acc} being accumulation mode aerosol number concentration and w being updraft velocity limited such that at w=16m/s CDNC= N_{acc}. The aerosol forcing in these simulations is highly idealized and is not intended to represent any sort of variation in aerosol properties in the same way as Easy Aerosol. The vertical velocity was set to have a minimum value of 0.1m/s. Ice number was controlled using a simple temperature-dependent relationship (Cooper, 1986). Because only two weeks of simulations were available for the UM-CASIM runs contours of SLP (as opposed to anomalies in SLP relative to the monthly-mean) were used to identify candidate cyclone centers as described in McCoy et al. (2018b).~~

3 Results

3.1 Precipitation and WCB moisture flux

The majority of moisture ingested into extratropical cyclones is imported along the warm conveyor belt (WCB) (Eckhardt et al., 2004;Field and Wood, 2007). The WCB moisture flux is defined as

$$WCB = k \cdot WVP_{CM} \cdot WS_{10mCM} \quad [3]$$

Where WVP_{CM} is the cyclone-mean water vapor path in kg/m^2 ; WS_{10mCM} is the cyclone-mean wind speed at 10 meters in m/s; and k is a constant parameterizing the width of the WCB as defined in Field and Wood (2007) and is calculated by linear regression of the precipitation rate on $WVP_{CM} \cdot WS_{10mCM}$. Cyclone means are the average of all data within a 2000 km radius of the cyclone center. We note that the k in Field and Wood (2007) was based on AMSR-E data. ~~It is likely that AMSR-E misses around 50% of the precipitation in extratropical cyclones~~AMSR-E observes half the precipitation rate in cyclones that Cloudsat does (Naud et al., 2018;Field et al., 2011). For consistency with previous literature we have chosen to use the k based on AMSR-E observations ($k = 2.66 \times 10^{-7}\ m^{-1}$,) as calculated by Field and Wood (2007). Our results might change slightly in a quantitative sense if another k was used, but will remain qualitatively the same. ~~In this study we will use $k = 2.66 \times 10^{-7}\ m^{-1}$, consistent with AMSR-E.~~

Although the moisture imported along the WCB may condense and form clouds within the cyclone, in order to maintain water mass balance in extratropical cyclones the moisture flux into a cyclone must match the precipitation out of the cyclone over a 2000 km radius. We ~~examine~~ find ~~whether~~ that ~~this~~ the product of WVP and wind speed within cyclones is a good predictor of precipitation rate ~~holds~~ in the ~~models~~ GCMs considered in this study~~listed in Table 2~~ ~~()~~.(Table 2~~Table 2~~ Fig. S1), in agreement with what has been found for observations(Field and Wood, 2007). ~~Field and Wood (2007) All the models show a very similar relationship between moisture flux into cyclones and precipitation rate averaged across the cyclone.~~ Thus the WCB flux is a proxy for the moisture flux into a midlatitude cyclone that is balance by the precipitation for quasi-steadystate. Model values of the WCB width parameter (k) (Eq. 3) range from $2.41 \times 10^{-7}\ m^{-1}$ to $4.11 \times 10^{-7}\ m^{-1}$ and are ~~generally higher than~~near to the k trained on AMSR-E data(Field and Wood, 2007). It is interesting to note that the k value does not appear to depend on model resolution and the lowest and highest k's come from the high resolution simulations in ICON and UM-CASIM, respectively. However, this range in k is within the observational uncertainty in precipitation rate(Field et al., 2011). Naud et al. (2018) examined observed precipitation rate in extratropical cyclone and found that the mean extratropical cyclone precipitation rate differed substantially depending on whether a microwave radiometer (0.08 mm/hr, AMSR-E) or radar (0.17 mm/hr, Cloudsat) was used to measure precipitation rate. If we rescale the AMSR-E precipitation rates so that the cyclone-mean precipitation rate is consistent with radar measurements, k should be $5.67 \times 10^{-7}\ m^{-1}$. Overall, the GCM cyclone precipitation flux that is predicted by the simple model of WCB moisture flux and the k inferred from the GCMs is well within the observational uncertainty.

~~Given the non-linear nature of Eq. 3, and the societal and economic importance of precipitation rates over the heavily populated NH midlatitudes,~~ WCB moisture flux provides a useful ~~constraint on~~predictor of precipitation- both in the climate mean-state and in projected changes in rain rate via dynamical alterations (in wind speed) and Clausius-Clapeyron driven changes (in WVP). We compare the distributions of WCB moisture flux, WS_{10mCM}, and WVP_{CM} in models and observations. The mean WCB moisture flux in the GCMs considered in this study is generally lower than the observations (Fig. S2~~1~~ ab), with model biases ranging from -1.16 mm/day to -0.31 mm/day in the SH and from -0.79 mm/day to +0.24 mm/day in the NH. This bias appears to be linked to low 10-meter wind speed in cyclones in models (Fig. ~~S1~~ S2 cd) as GCM WVP_{CM} is near to the observed distribution (Fig. ~~S1~~ S2 ef). One possibility is that this issue is related to excessive surface drag over oceans, which is a known issue in modelling tropical cyclones(Donelan et al., 2004;Soloviev et al., 2014). Anecdotally, the CNRM-CM6 LR and HR GCMs cap surface drag and are the only two GCMs whose mean wind speed is greater than or equal to the observed wind speed. Based on this we suggested sensitivity tests in GCMs to the capping of surface drag as a step toward a realistic representation of midlatitude precipitation rates. If this is the cause of lower surface wind speed in cyclones then it means that modelled midlatitude cyclones have been systematically under-estimating precipitation through decreased flux of moisture into the cyclone. It is also possible that the low WS_{10mCM} in some of the GCMs reflects deficient horizontal resolution (Strachan et al., 2013). The most biased cyclone-mean WS_{10m} speeds are the IPSL-CM5 and CNMR-CM5 models, which have relatively low horizontal resolutions~~, but th~~. This may be concidental as there does not appear to be a systematic trend ~~in~~ in~~as horizontal resolution increases in~~ different resolution instances of the same model within the PRIMAVERA GCMs.

3.2 LWP and WCB moisture flux

As shown in section 3.1, precipitation within midlatitude cyclones is predicted by WCB moisture flux. ~~This means that cyclones are in an approximate steady state because the flux of moisture into the cyclone is matched by the flux of precipitation out of the cyclone. In this study we will examine how this steady state varies across GCMs and observations. In particular, we will examine the transition of water vapor to precipitation through its intermediary state suspended in cloud droplets.~~This provides a useful way to understand changes in cyclone properties as it gives a predictor of precipitation rate that can be decomposed into a contribution from dynamics (the wind speed) and thermodynamics (the WVP).

In McCoy et al. (2018b) it was proposed that when averaged over a sufficiently long period of time cyclones were in a steady state where the environment- in particular the moisture flux- dictated the precipitation rate out of the cyclone.

If extratropical cyclones are in steady-state, then we expect that an increased moisture flux should enhance cyclone LWP, providing that precipitation processes are dominated by the warm rain process. This is because a higher in-cloud LWP is needed to generate a higher rain rate below cloud (Wood et al., 2009;Hill et al., 2015). Thus, areally-averaged rain-rate should increase as LWP increases either by increasing coverage of cloud, or by increasing in-cloud LWP. ~~We will elaborate on this assumption shortly.~~ Both~~Enhanced cyclone LWP should either increase in-cloud LWP or increase cloud coverage. Both~~ effects should translate to an enhancement in cyclone albedo (at a fixed solar zenith angle, see the discussion in McCoy et al. (2018b)). This makes understanding the efficiency with which extratropical cyclones can convert moisture flux to precipitation via cloud water key in understanding variability in extratropical albedo. We note that in this study we utilize microwave observations of LWP, which are the average of cloudy and clear regions, so increases in either *in-cloud* LWP or cloud coverage should translate to an increase in microwave-observed LWP. Similarly, the GCM LWP is the average of clear and cloudy regions.

Extratropical cyclone LWP represents a key variable in determining extratropical albedo, but does it scale with WCB moisture flux? A linkage between moisture flux into an extratropical cyclone and the total column liquid in the cyclone has been demonstrated previously in McCoy et al. (2018b). A caveat to this is that in McCoy et al. (2018b) total liquid water path (TLWP, precipitating and non-precipitating liquid) was examined. Here, we examine the fraction of the TLWP which is suspended in clouds (referred to as LWP, here).

Does LWP_{CM} increase with WCB moisture flux in the same way that $TLWP_{CM}$ does? The efficiency with which extratropical cyclones can shift vapor to rain determines the relation between WCB moisture flux and LWP_{CM}. In the limiting case this efficiency might increase sufficiently rapidly with moisture flux that LWP_{CM} would not increase in step with WCB moisture flux (all additional liquid becomes rain). Because we cannot directly observe how extratropical cyclones partition precipitating and non-precipitating liquid (see methods section), we cannot directly evaluate how precipitation efficiency scales with WCB moisture flux. This represents an uncertainty in our analysis. However, we can evaluate extratropical cyclone rain and cloud partitioning in high-resolution simulations as a check on the caclulations used in the MAC-LWP dataset. LWP_{CM}, $TLWP_{CM}$ (rain+cloud liquid), and WCB moisture flux are calculated for extratropical cyclones observed using MAC-LWP and as simulated by UM-CASIM (see Table 2~~Table 2~~). The parameterization that partitions cloud and rain water paths in the MAC-LWP observations results in a decrease in~~s~~ the fraction of ~~total~~ liquid water path that is in clouds ($LWP_{CM}/TLWP_{CM}$)

as WCB moisture flux decreases by -0.075 day/mm (see the slope of the line in Fig. S2S3). Comparison to UM-CASIM simulations shows a similar decrease in the fraction of liquid water that is suspended in clouds (-0.087 day/mm, Fig. S2S3). Ultimately, the partitioning of rain and cloud water in MAC-LWP, and the microphysics scheme in UM-CASIM both lead to an increase in LWP with increasing WCB moisture flux. McCoy et al. (2018b).This is likely due to autoconversion becoming more efficient at higher LWP leading to a more pronounced flattening of the curve at higher LWP. It was shown in McCoy et al. (2018b) that this behavior could be fit as $LWP \propto WCB^p$ or $LWP \propto RR^p$, where RR is rain rate, since WCB moisture flux and rain rate are linearly related. Conceptually, we should expect this based on the warm rain process. To reiterate, a greater LWP is required to yield a larger precipitation(Wood et al., 2009;Hill et al., 2015), which is in turn needed to match the moisture flux into the cyclone.

We have examined how WCB moisture flux predicts precipitation. We have also examined how the partitioning between rain and cloud changes as a function of WCB moisture flux. Now we will embark on an examination of the relationship between WCB moisture flux and LWP. WeWith the caveat in mind that we must infer the partitioning of liquid between rain and cloud, we evaluate the ability of a wide array of GCMs to simulate the response of cyclone-mean LWP (LWP_{CM}) to WCB moisture flux. will focus on the behavior of cyclones within the SH. This is done for the following reasons: (1) the SH has a large, unbroken expanse of midlatitude ocean to investigate; (2) GCMs have well-documented and ongoing issues in accurately representing cloudiness in these regions(Trenberth and Fasullo, 2010;McCoy et al., 2016;Grise et al., 2015); (3) the GCM-predicted negative cloud optical depth feedback that is the primary subject of this paper is most pronounced in the SH(Zelinka et al., 2012a;Zelinka et al., 2016); and (4) observations and GCMs show a robust trend in LWP in this region that is likely driven by warming (Manaster et al., 2017;Norris et al., 2016). Ultimately, we focus on the SH for the sake of brevity. We find extremely similar behavior in the NH and the plots in the paper are reproduced in the supplementary material for the NH.

With the caveat in mind that we must infer the partitioning of liquid between rain and cloud in the observations, we evaluate the ability of a wide array of GCMs to simulate the response of cyclone-mean LWP (LWP_{CM}) to WCB moisture flux in the Southern Ocean (30°-80°S). We compare the WCB moisture flux dependence of LWP_{CM} in the models listed in Table 2Table 2 and observations from MAC-LWP (Fig. 1Fig. 1). Increasing WCB moisture flux increases LWP_{CM} in both observations and models. As noted above, Conceptually, we should expect this based on the warm rain process. To reiterate, aA greater LWP is required to yield a larger precipitation rate (Wood et al., 2009;Hill et al., 2015). As shown in section 3.1 precipitation rate is well-predicted by the WCB moisture flux, which is in turn needed to match the moisture flux into the cyclone. —While the high-resolution models (<100km horizontal resolution) have a slope of the WCB-LWP_{CM} relationship that is in keeping with the observed slope,. Tthey tend to have too low a LWP_{CM} for a given WCB moisture flux. However, if the maximum bias in observed LWP_{CM} of 0.03 kg/m^2 is assumed based on an estimated range 0.01-0.02 kg/m^2 (Greenwald et al., 2018), then many of these models are in the possible observational range. It is also reasonable to suspect that models that only generate clouds when the entire grid box is saturated (e.g. there is no convection parameterization or cloud scheme) will under-estimate cloudiness.

It is suggestive that the lower-resolution CFMIP2 models tend to have a much wider diversity in slopes than the higher resolution PRIMAVERA models, UM-CASIM, NICAM, and ICON. This may reflect parametric uncertainty in the representation of convection. UM-CASIM, NICAM, and ICON do not parameterize convection and have extremely similar relationships between WCB moisture flux and LWP. Based on this we suggest that the relationship between moisture flux and LWP may offer a possible evaluation tool for the realism of convection within GCMs. However, this may also just be chance related to the selection of models presented here as the low-resolution HadGEM3-GC31-LM has a reasonably close behavior to the higher resolution instances of that model (HadGEM3-GC31-MM, and HadGEM3-GC31-HM). Overall, the constraint provided by the WCB-LWP_{CM} relationship shown here provides a useful tool for GCMs to evaluate their climate mean-state behavior in the extratropics.

As discussed in the paragraph above, the partitioning between rain and cloud ~~liquid~~ shifts toward rain at higher moisture fluxes (Fig. ~~S2~~S3). This leads to the asymptotic nature of the curves shown in Fig. 1~~Fig. 1~~. Presumably differences in the degree to which the curve flattens at higher LWP as precipitation becomes more efficient in some models ~~Presumably this~~ reflects differences in the way that precipitation is treated in the different GCMs with (for example) autoconversion being stronger in some models leading to a more pronounced flattening of the LWP-WCB curve (and vice-versa)~~models leading to a more pronounced flattening of the curve at higher LWP as precipitation becomes more efficient~~. ~~In this work we will treat the~~The asymptotic behavior of the WCB-LWP_{CM} curve i~~as~~ s a second order effect ~~for the sake of simplicity~~ in our analysis (we will return to this discussion in section 3.3.3). ~~However, we note that this behavior does provide a useful evaluation of the precipitation processes in a given model and more in-depth examination of this feature is reserved for a future study.~~

3.3 Long-term variability in observed cloud properties

3.3.1 Monthly-mean regional variability in extratropical cyclone properties

The moisture flux into extratropical cyclones plays a dominant role in determining their LWP and, ultimately, precipitation rate. How does this mechanism influence the cloud feedback in the midlatitudes? In keeping with earlier studies(Myers and Norris, 2016;Qu et al., 2015) we examine observed anomalous variability from 1992-2015 to infer the cloud feedback in these regions within cyclones. We will then utilize transient warming simulations where SSTs have been increased by 4K to see if variability within the current climate has the capability to predict the change in cyclone properties in a warmed climate. This technique follows the analysis of stratocumulus clouds in Qu et al. (2015). The Indian, Pacific, and Atlantic oceans between 30°S-80°S~~; and Atlantic, and Pacific oceans poleward of 30°-80°N~~ are each examined individually (precise regions are shown in Fig. S4). In this section we discuss cyclone-means in the context of the monthly-means across all the cyclones in each region. For each region the monthly-mean anomaly relative to the monthly-mean climatology is calculated. Variables averaged to regional means are denoted RM (see Table 1~~Table 1~~ for a list of acronyms and subscripts).

~~Before we discuss analysis of anomalous variability in extratropical cyclones, we want to note that in McCoy et al. (2018b) $TLWP_{CM}$ (rain and cloud) was fit using the form $TLWP_{CM} = a \cdot WCB^{b} CDNC_{SW}^{c} + d$, where $CDNC_{SW}$ was the average cloud droplet number concentration (CDNC) within the southwest quadrant (in poleward coordinates, alternatively equator-westward) and WCB was WCB moisture flux. As shown in Fig. 3, there is a power-law relationship between LWP_{CM} and WCB moisture flux across observations and models. Here we will linearly relate monthly-mean anomalies in LWP_{RM} to~~

regional- and monthly-mean anomalies in WCB moisture flux. A linear relation is used in this case because the anomalous variability is relatively small (compared to the overall variability) and the relation between monthly-mean anomalies in LWP_{RM} and anomalies in regional- and monthly-mean WCB moisture flux is approximately linear.

Fig. 2Fig. 2 shows the relation between the regional- and monthly mean of of various cyclone properties. For example, we may ask if across a given ocean basin in a given month the LWP within cyclones is higher when WCB moisture flux into cyclones is higher (Fig. 2a). For each ocean basin () the average of the LWP_{CM} for all cyclones for each month is taken (LWP_{RM}). The climatological LWP_{RM} is subtracted for each month to yield anomalies. The same procedure is repeated for WCB moisture flux. The relation between anomalies in LWP_{RM} and WCB moisture flux anomalies is shown in Fig. 2Fig. 2a. This allows us to examine the relation of various predictors across the population of cyclones within a given basin in the Southern Ocean.

Anomalous variability in LWP_{RM} in the SH extratropical oceans correlated correlates with variability in WCB moisture flux (28-42%, Fig. 2Fig. 2a). The South Pacific region has 42% of monthly-mean LWP_{RM} anomalies explained by moisture flux anomalies, the South Atlantic and Indian Oceans have approximately 30% of their monthly anomalies in LWP_{RM} explained by moisture flux. Overall, the slope of the relation between anomalies in monthly-mean extratropical cyclone LWP_{RM} and WCB moisture flux monthly means are quite similar across these regions and the slope has very little uncertainty. As discussed above, the methodology here assumes linearity in the change in LWP_{RM} in response to anomalies in regional and monthly-mean WCB moisture flux. One possibility to explain the range of R^2 across basins is that larger ranges in WCB moisture flux may lead to non-linearity in the relationship and thus a lower R^2 for the fit between anomalies in LWP_{RM} and WCB. However, the range of WCB anomalies is only slightly smaller in the SH (Fig. 5bc).

Why do the different ocean basins have such different explained variances (R^2's) in the relationship $LWP_{RM} = a \cdot WCB_{RM} + c + resid$? Presumably this relates to some unconsidered predictor in our analysis expressed through the residual term. For example, McCoy et al. (2018b)CDNC variability in cyclones substantially affects LWP(McCoy et al., 2018b). The explained variances in the different ocean basins are consistent with this. The explained variance by WCB moisture flux is higher in the South Pacific compared to the rest of the Southern Ocean where intermittent phytoplankton blooms dramatically vary CDNC(McCoy et al., 2015a;Meskhidze and Nenes, 2006;Charlson et al., 1987) and the NH where anthropogenic emissions vary from year to year(McCoy et al., 2018a;Bennartz et al., 2011). It is also interesting to speculate on the potential effect of variability in cloud condensation nuclei (CCN) on the relationship between WCB moisture flux and LWP across basins. Enhanced CCN enhances cloud droplet number concentration (CDNC) and inhibits the warm rain process in cyclones and enhances LWP at a given WCB moisture flux (McCoy et al., 2018b). Thus, anomalous inter-annual variability in CCN would could diminish the fraction of the variance explained by WCB moisture flux alone (e.g. decrease R^2). As shown in previous studies, the primary source of variability of CCN in the Southern Ocean is biogenic sulfate (Ayers and Cainey, 2007;Ayers and Gras, 1991;Meskhidze and Nenes, 2006, 2010;Charlson et al., 1987). The Pacific basin of the Southern Ocean is less biologically productive and does not have the intense phytoplankton blooms present in the Atlantic basin(McCoy et al., 2015a). It is possible that the low summer-summer variability in biogenic CCN in the Pacific leads to a greater fraction of the 1992-2015 anomalous monthly variability being explained by meteorological drivers, while the intense, but intermittent blooms and accompanying CCN in the South Atlantic and Indian Oceans may diminish the fraction of total variability contributed by meteorology.(McCoy et al., 2018a) The global climate models that we focus on in this study to do not provide CDNC as an output and we will reserve partitioning inter-annual variability in cyclone behavior into contributions from meteorology and microphysics for future study.

It is interesting to contrast the SH ocean basins with the northern Atlantic and Pacific (Fig. 5a). Only 30% of North Pacific and North Atlantic monthly-mean LWP_{RM} variability is explained by WCB moisture flux. However, the best fit line in the NH oceans is similar to the best fit in the SH oceans - indicating that the WCB-moisture flux mechanisms are likely to be at work controlling inter-annual variability, but is not as relevant in relation to observed anomalous variability in monthly-mean LWP_{RM} in the last two decades. It may be that strong year-year variability in anthropogenic sulfate, and thus CDNC, in the NH ocean basins(McCoy et al., 2018a) reduces the fraction of anomalous variability that is explained by moisture flux alone. In fact, pollution control measures in both East Asia and North America have led to a steady downward trend in CDNC across their midlatitude outflow regions in recent years (McCoy et al., 2018a;Krotkov et al., 2016), following a period of enhancing CDNC from 1980-2005 off the coast of China (Bennartz et al., 2011). The effects on LWP from the trend in CDNC over the period 2005-2015 off the coast of East Asia and from 1992-onwards off the east coast of North America should oppose the effects from the trend in WCB moisture flux. This is because decreased CDNC should decrease LWP for a given WCB moisture flux, and as discussed below, moisture flux will be enhanced by Clausius-Clapeyron-driven enhancement in WVP as the oceans and atmosphere warm. Enhancement in WCB moisture flux should enhance cyclone LWP. Thus, the meteorologically-driven trend and microphysically-driven trends in these regions are likely to be opposed, at least in the last decade. Finally, we may speculate that land-ocean interactions in the NH affects cyclone properties via mechanisms such as cold-air outbreaks, which may in turn affect LWP (McCoy et al., 2017c).

We should also note that cyclones at low latitudes are likely to be transitioning from tropical to extratropical cyclones. Tropical cyclones differ in their meteorological drivers and the WCB moisture flux mechanism is not relevant to their development (Emanuel, 2003). If only cyclones centered between 35°-80° latitude are considered, the variance explained in LWP_{RM} by WCB moisture flux increases from 30-42% to 36%-46% (Fig. S3). However, the correlation between anomalies in WCB moisture flux and LWP_{RM} are significant at 95% confidence, regardless of the latitude range considered. Field and Wood (2007)

A large fraction (~1/3) of SH ocean anomalies in monthly- and regional-mean LWP_{RM} and, ultimately, 32% of anomalous monthly-mean LWP_{RM} variability across all basins may be explained by WCB moisture flux anomalies alone and the sensitivity of LWP to WCB moisture flux is robust and differs very little from basin to basin (weighting each basin equally in the linear regression). What in turn explains moisture flux variability? As shown in Eq. 3, WCB moisture flux is the product of WVP and wind speed. We will discuss the contributions of each of these terms below.

Monthly-mean cyclone WS_{10mRM}, which is a proxy for the input rate of moisture into the cyclone, enhances as cyclones move poleward in both hemispheres (Fig. 2Fig. 2b and Fig. S4S6). In the Southern Oceans and North Atlantic 1836-55% of anomalous monthly variability in wind speed is linearly related to cyclone poleward latitude- in the North Pacific only 18% of anomalous variability in wind speed may be explained by mean cyclone latitude. Examination of cyclone-mean wind speed as a function of latitude shows agreement in models and observations. In models and observations cyclone-mean wind speed increases toward 60°, and then decreases poleward of 60° in both hemispheres (Fig. ~~S4~~S6). Overall, the explained variance in anomalous monthly- and regional-mean wind speed is ~~41~~49% across all SH ocean basins (weighting all ocean basins equally). This reflects the genesis and development of an extratropical cyclone. The genesis of extratropical cyclones occurs toward the tropics and then over their life cycle cyclones move toward the pole. During this life cycle they intensify, leading to enhancement in near-surface wind speed (Tamarin and Kaspi, 2017;Beare, 2007;Bengtsson et al., 2009). Two important questions stand out in regards to our analysis: Will the genensis region of extratropical cyclones shift in a warmed climate? ~~How will~~Will extratropical cyclones develop differently in a warmed climate?

The complexity of changes in the life cycle, frequency, and intensity of extratropical cyclones under warming makes it difficult to say confidently how their vorticity and surface wind speed will change. There is a general consensus that storm tracks will shift toward the poles as the climate warms(Barnes and Polvani, 2013;Yin, 2005;Lorenz and DeWeaver, 2007;Bender et al., 2011b), but the mechanism that prompts this poleward movement remains unclear (Shaw et al., 2016). As they shift poleward storm tracks intensify(Lorenz and DeWeaver, 2007;Yin, 2005;Ulbrich et al., 2009). ~~Alterations in tropopause height have been suggested as the mechanism underlying this change(Lorenz and DeWeaver, 2007). The relationship between storm track behavior and cyclone behavior adds additional complexity. Ulbrich et al. (2009) provides a thorough review of studies investigating changes in extratropical cyclone intensity, placement, and population in warmed climates.~~ Simulations with green house gas warming generally show decreased frequency of midlatitude cyclones, but increases in cyclone intensity (Lambert and Fyfe, 2006;Bengtsson et al., 2006;Geng and Sugi, 2003). This may be related to changes in cyclone lifecycle with cyclones taking longer to reach peak intensity over a longer propogation in a warming world~~Changes in extratropical cyclone life cycle further complicates predicting changes in cyclone wind speed in a warming world. Utilizing a single highly idealized GCM Tamarin and Kaspi (2017) demonstrate that extratropical cyclones not only shift poleward, but take longer in their development in a warming world with peak intensity being reached after a greater poleward propogation~~ (Tamarin and Kaspi, 2017;Tamarin-Brodsky and Kaspi, 2017). ~~Further investigation within the CMIP5 models by Tamarin-Brodsky and Kaspi (2017) demonstrated that this is a robust feature of GCMs and is not limited to highly-idealized models. Overall, the complexity of changes in the life cycle, frequency, and intensity of extratropical cyclones under warming makes it difficult to say confidently how their vorticity and surface wind speed will change. It is interesting to speculate that substantial changes in cyclone voriticity might have occurred in past cold climates such as the Maunder minimum (Raible et al., 2007). We reserve further evaluation of changes in cyclone wind speed in high-resolution simulations for integration of the warming simulations as part of PRIMAVERA.~~ We will discuss the ~~climate~~ response to a transient warming within CFMIP2 GCMs where the prescribed SST is enhanced by 4 K in the following section.

Monthly-mean variability in extratropical cyclone ln(WVP)$_{RM}$ is explained by SST$_{RM}$ with ~~76~~80% of anomalous monthly mean variability in ln(WVP)$_{RM}$ ~~linked to~~predicted by ~~ln(~~SST$_{RM}$~~)$_{RM}$~~ (Fig. 2~~Fig. 2~~c). ~~The explained anomalous variance in individual ocean basins is greater than 70%, with the exception of the North Pacific, where it is 65%.~~ This linkage between anomalies in cyclone-mean SST and anomalies in ln(WVP) via Clausius-Clapeyron has been shown previously in Field et al. (2008).

In summary, w~~W~~e propose that Southern Ocean cloud feedbacks in cyclonic systems are not only related to the so-called mixed-phase cloud feedback, but are contributed to by changes in WVP and wind speed. Because increasing SST increases WVP via Clausius-Clapeyron, which in turn increases condensed water, this response to increasing SST ~~it~~ is easy to conflate ~~it~~ with ice to liquid transitions ~~driven by SST increases~~. However, SST alone is a poor predictor of LWP_{RM} (Fig. S7). The variance in LWP_{RM} explained by SST alone is less than 10% in any basin and the fits in the different basins are different at 95% confidence. This is consistent with the weak negative dependence of cloud optical depth on SST shown by Terai et al. (2016). In the following sections we will continue to investigate the dependence of cyclone LWP on WCB moisture flux in the current climate and investigate how this mechanism might affect the extratropical cloud feedback. ~~We will examine this hypothesis in the following sections.~~

3.3.2 ~~Global m~~Model-observation comparisons of extratropical cyclone behavior

As shown above, observed extratropical cyclone LWP_{CM} depends ~~strongly~~ on WCB moisture flux. This translates to anomalous regional- and monthly-mean variability in WCB moisture flux ~~strongly~~ covarying with regional- and monthly-mean anomalous variability in extratropical cyclone LWP_{RM}. As we saw in Fig. 1~~Fig. 1~~, climate model extratropical cyclone LWP also depends on WCB moisture flux, but models do not agree on how sensitive cyclone LWP_{CM} is to moisture flux. In this section we examine how GCM regional- and monthly-mean anomalous variability in extratropical cyclone properties compares to observations within the current climate.

First, we examine the ability of models to reproduce the WCB moisture flux-LWP_{RM} relation observed in the SH. As in Fig. 2~~Fig. 2~~a, the slope of the best fit linear line between monthly-mean anomalies in cyclone LWP_{RM} and WCB moisture flux is computed in each SH ocean basin, and is summarized in Fig. 3~~Fig. 3~~a. The 95% confidence on the best fit line is also shown. All the models and the observations have a non-zero slope at 95% confidence. The slope of the WCB moisture flux LWP relationship in IPSL-CM5B-LR, and CNRM-CM5 models are more than twice the slope inferred from observations, while the CNRM-CM6 and HadGEM3 models have around half the observed slope. NICAM, HadGEM2, IPSL-CM5A-LR, and the EC-Earth models compare favorably to the observations. Evaluation of model variability shows that all models have over 20% of their LWP_{RM} variability explained by WCB in the SH, with some models able to explain up to 70% of their anomalous monthly- and regional-mean variability using WCB moisture flux (Fig. ~~S5~~S8). Despite low explained variance in some models, the relationship between WCB moisture flux and LWP is significant at 95% confidence in all of the models. As discussed in the previous section, variability in warm cloud microphysics (eg. CDNC) has been shown to substantially affect cyclone LWP(McCoy et al., 2018b). The inclusion of these or other processes as predictors should increased explained variance by the regression model. For example, NICAM, which has no aerosol-cloud adjustments has the highest variance explained by WCB moisture flux alone (50%-75%, depending on the basin, Fig. S8). Overall, the variance explained in the current climate is of secondary interest to the confidence in the slope of the relationship.

Next, we investigate the relation between mean absolute (poleward) cyclone latitude and WS_{10m} in cyclones. All models have a correlation between anomalous monthly-mean poleward latitude and WS_{10mRM} at 95% confidence (Fig. 3~~Fig. 3~~b), in keeping with the agreement in the latitudinal dependence of WS_{10mCM} shown in Fig. ~~S4~~S6. The agreement between the observered and modeled sensitivities is good and most models overlap with the 95% confidence on the observational sensitivityGCMs tend to have a higher sensitivity to mean cyclone latitude than the observations, but are in good overall agreement.. This supports the idea that the models presented here have a fairly consistent representation of the cyclone life cycle in the current climate.

Finally, we examine the relation between ln(WVP)$_{RM}$ and SST $_{RM}$ in the GCMs as in Field et al. (2008). The relation between SST and column water vapor in the models and in the observations are quite similar (Fig. 3Fig. 3c), indicating that all the models are able to somewhat accurately reproduce the response in WVP associated with Clausius-Clapeyron and warming.

3.3.3 Decadal trends in extratropical cyclone properties

We haveIn section 3.3.1 and 3.3.2 we discussed how monthly anomalies variablity in LWP$_{RM}$ may be explained predicted by moisture flux. This examination of the variability within the system supports suggests the idea thatthat the warming will lead to enhanced LWP across the midlatitude ocean via enhanced WVP that may be fluxed into cyclones. This means that the shortwave cloud feedback in the Southern Ocean (SO) may be partially driven by changes in meteorology WCB moisture flux and not only by ice to liquid transitions. To support this argument we examine whether warming on a decadal scale across the midlatitudes is accompanied by an increase in WCB moisture flux and cyclone LWP. This LWP behavior has already been shown within the data record. -Examination of zonal-mean LWP anomalies in the MAC-LWP data record and in GCMs by However, the robust decadal trend in zonal-mean LWP in the SO observed by Manaster et al. (2017) still needs to be discussedshowed a robust positive trend in LWP. In this section Analysis of the decadal trend in observational record to infer climate response would interpret this as confirmation for a negative shortwave cloud feedback in the SO. However, it is unclear what has caused this change in LWP. Wwe will now examine the trend in cyclone LWP during the period 1992-2015 in the context of trends in moisture flux. This will be contrasted with the zonal-mean trend diagnosed by Manaster et al. (2017).

First, iIn this study we are pursuing a regime-oriented approach to understanding extratropical variability. Do the zonal-mean trends in Manaster et al. (2017) agree with the trends in extratropical cyclone behavior? Because Manaster et al. (2017) investigated trends in the latitude band 44.5°S-59.5°S we subset our data record to only consider cyclones centered in this latitude band so that a more direct comparison can be made. Trends in Southern Ocean regional-mean cyclone LWP$_{RM}$ and zonal-mean LWP as calculated by Manaster et al. (2017) over the last two decades are similar (Fig. 4Fig. 4ab, 2.40±0.58 g m^{-2} decade^{-1} within extratropical cyclones versus 1.8±0.8g m^{-2} decade^{-1} in the zonal-mean(Manaster et al., 2017), where uncertainty is the 95% confidence interval).

Given that cyclones cover approximately half the Southern Ocean (Bodas-Salcedo et al., 2014), this in-cyclone trend can account for a good portion of the overall zonal-mean signal.

We have shown in the previous section that around a third of the monthly- and regional-mean variability in cyclone LWP$_{CM}$ is related to variability in WCB moisture flux (Fig. 2Fig. 2a). A regression on SST alone explains less than a tenth of the variance (Fig. S7). Consistent with this, we could use the simple regression model $LWP_{CM} = a \cdot WCB + c + resid$ trained on the observational record to see if the LWP trend in the Southern Ocean is consistent with the trend in WCB moisture flux. It is possible that there is some component of this trend that is related to changes from ice to liquid phase that is being obscured by WCB moisture flux variability. Both changes from ice to liquid and the WCB moisture flux (via WVP and Clausius-Clapeyron) will be associated with variability in atmospheric temperature. To examine this we need to disentangle changes related to the synoptic state and changes in SST in the observational record. How does this trend partition into components related to meteorology (as characterized by WCB moisture flux) and thermodynamics (as characterized by SST)? We investigate attempt this utilizing a simple regression model fitting to a two-dimensional plane in WCB moisture flux and SST space. This fit splits the variability into a WCB moisture flux term and a term associated with SST variations around a given WCB moisture flux (Fig. 5Fig. 5). If changes from ice to liquid water are an important factor in the cloud feedback in this region, then increasing SST at a fixed WCB moisture flux should correspond to an increase in LWP.

Regressing on WCB moisture flux and SST simultaneously is cumbersome as SST changes ultimately drive a significant fraction of WCB moisture flux changes via Clausius-Clapeyron. Analogously, SST and atmospheric stability covary, but have differing effects on cloud cover and similar linear regression analysis has been undertaken to disentangle their contributions and infer the shortwave cloud feedback (Qu et al., 2015;Klein et al., 2017;Terai et al., 2016). (Bretherton and Blossey, 2014)(McCoy et al., 2017a)

To try and partition variance in the Southern Ocean into components related to synoptic variability and a component related to the variance in SST around the synoptic state we train the regression model

$$LWP_{CM} = a \cdot WCB + b \cdot SST_{CM} + c + resid \qquad [4]$$

This regression model is trained on the population of SH cyclone-means from 1992-2015 and centered in the latitude band considered in Manaster et al. (2017). In this analysis we ignore the power law dependence of LWP on WCB moisture flux (Fig. 1Fig. 1). (McCoy et al., 2018b)In the following section we show that this assumption does not substantially affect the predictability of the change in cyclone LWP in response to warming. It does not capture some of the power-law behavior in the WCB moisture flux-LWP relationship, but it simplifies the interpretation of the anomalous variability. The regression model trained on the observational record has coefficients

$$LWP_{CM} = (28.71 \pm 0.42) \cdot WCB - (0.29 \pm 0.1) \cdot SST_{CM} + 3.70 \pm 1.21, n = 18842, R^2 = 0.53 \qquad [5]$$

As can be seen in Fig. 5Fig. 5 LWP_{CM} primarily depends on WCB moisture flux. At a fixed WCB moisture flux changes of ±5K in the SST do not correspond to significant changes in LWP. Because of this The trend in regional- and cyclone-mean LWP predicted based on this regression model and changes in SST are relatively slight (Fig. 4bc)- most most of the long-term trend in LWP_{CM} averaged across the Southern Ocean can be explained by changes in WCB moisture flux alone (Fig. 4Fig. 4bd). This is not to say that changes in SST do not have any effect- cleary they do via the WVP term in the WCB moisture flux. Most of the increase in WCB moisture flux may be explained by steadily increasing cyclone WVP, driven by enhanced SST (Fig. S9). However, changes in SST independent of WCB do not predict the trend in LWP. In turn, most of the increase in WCB moisture flux may be explained by steadily increasing cyclone WVP, driven by enhanced SST (Fig. S6). The steady enhancement of SST across the Southern Ocean is driven by anthropogenic forcing (Liu and Curry, 2010).This is also shown in schematic form in Fig. 5Fig. 5: between 1992 and 2015 SST increases and WCB moisture flux increases, driven by Clausius-Clapeyron, but the shift in SST has relatively little effect independent of the shift to higher WCB moisture flux.

The regression model in Eq. 5 uses variability in WCB moisture flux and SST to predict variability in cyclone LWP. As discussed above, SST variability drives changes in WVP via Clausius-Clapeyron, leading to covariability between It is important to state the caveat that WCB moisture flux and SST_{CM} are fairly colinear (r=0.84 over the 1992-2015 period in both hemispheres, see also the contours of cyclone population in Fig. 5Fig. 5). While WCB moisture flux and SST_{CM} are fairly colinear, SST_{CM} is only poorly correlated with LWP_{CM} (r=0.25). The correlation between LWP_{CM} and WCB moisture flux is much stronger (r=0.63). As discussed in section 3.3.1, the correlation between monthly- and regional-mean anomalies in SST and LWP are also weak and are inconsistent between basins. Thus, despite being a good predictor of the WVP component of WCB moisture flux, SST_{CM} it is a poor predictor of cyclone LWP_{CM}, which is consistent with the lack of a trend associated with SST variability independent of WCB moisture flux variability in Fig. 4Fig. 4.

However, despite variance being shared between SST and WCB moisture flux, theThe coefficient relating WCB moisture flux and LWP in Eq.5 is relatively insensitive to whether or not SST is included as a predictor. If WCB moisture flux is used as the only predictor, then the coefficient relating WCB moisture flux to LWP changes to 28.13±0.40 g m^{-2} day mm^{-1}. If only SST is used as predictor, then the coefficient relating SST and LWP changes sign (+2.90±0.12 g m^{-2} K^{-1}). This is because SST is a good predictor of WCB moisture flux so if WCB moisture flux is not held constant in the regression the coefficient relating SST to LWP absorbs variability related to WCB moisture flux. (Qu et al., 2015;Klein et al., 2017)(Wood and Bretherton, 2006)(Qu et al., 2014)Based on this we feel that the relationship between WCB moisture flux and LWP as inferred by multiple linear regression is fairly robust, despite sharing significant variability with SST.

This also shows that studies using SST alone to infer the climate feedback in this region will lead to non-robust predictions of the change in LWP because SST will covary with WCB moisture flux in the mean climate, but the change in SST in response to green house gas-driven warming will not be the same as the change in WCB moisture flux. This argument infers the change in LWP from current variability- to further support this analysis we will turn to transient warming simulations in section 3.3.4.Based on this we feel that the relationship between WCB moisture flux and LWP as inferred by multiple linear regression is fairly robust, despite sharing significant variability with SST.

It appears that oOnce the trend in WCB moisture flux is accounted for relatively little room is left for an effect related to phase changes (Fig. 4Fig. 4b). SST was included as a predictor in Eq. 4 to see if variations in SST at a constant WCB moisture flux led to an increase in LWP consistent with a transition from ice to liquid. It was found that SST increases corresponded to a slight decrease in LWP at a given WCB moisture flux. This is consistent with SST acting as a proxy for several other boundary layer processes such as weakening the inversion strength and the buoyancy driven reductions in cloud cover(Bretherton and Blossey, 2014). OverallSST may not act as a good predictor of the ice-to-liquid transition, but the residual trend unrelated to SST trends or WCB trends is small. That is to say, we cannot take the trends in the observational record of cyclone LWP as a sign of a strong mixed-phase cloud feedback because most of the trend is explained predicted by changes in synoptic state. (WCB~WS*WVP~WS*SST^q) driven by sst changes….

Comparison of the trend in Southern Ocean LWP_{RM} for the models listed in Table 2~~Table 2~~ are shown in Fig. 4~~Fig. 4~~b. Despite the models being run in AMIP-mode with prescribed SSTs, there is significant variability in the trend in LWP_{RM} in the period 1992-2015 (note that CFMIP2 models simulated 1979-2008). The GCMs all show a positive trend that is significant at 95% confidence, but generally under-predict the strength of the trend. It is also interesting to note that the trend in LWP_{RM} across the Southern Ocean is almost completely explained by WCB moisture flux variability in all the GCMs. In the following section we will revisit this puzzle and use spatial variability within cyclone composites and cloud top phase to attempt to disentangle the contributions of ice-to-liquid transitions and WCB moisture flux. ~~We will support the observationally inferred importance of WCB moisture flux in a warming climate using GCM simulations with artificially enhanced SST below.~~

Of course this only examines variability within extratropical cyclones. One possibility is that in anti-cyclones all long-term trends relate to phase transitions consistent with the mixed-phase cloud feedback. However, this seems unlikely given the extensive analysis performed by Terai et al. (2016) demonstrating a substantial contribution to cloud optical depth variability in the Southern Ocean from variability in estimated inversion strength (EIS, Wood and Bretherton (2006)), and a lesser contribution linearly related to SST. It is also worth noting that increased SST predicted ~~was found to decrease or increase cloud optical depth, depending on the observational data and season examined~~decreased cloud optical depth (Terai et al., 2016). Thus, it is unlikely that all the trend in anti-cyclonic regions is related to phase transitions and it is more likely that the trend in these regions is dominated by trends in boundary-layer cloudiness consistent with enhancing inversion strength(Terai et al., 2016), which is a well-quantified feature of boundary-layer cloud cover(Wood and Bretherton, 2006;Klein and Hartmann, 1993). We reserve a more complete examination of cloud variability composited around both high and low pressure centers for a future paper and will focus on examining low pressure centers in the present work.

The WCB moisture flux and cyclone LWP are covariable (Fig. 2a). This infers that warming over the midlatitudes should result in an increase in LWP as WCB moisture flux increases following Clausius-Clapeyron. The trend in cyclone LWP over the Southern Ocean in response to warming agrees with this inference made from internal variability (Fig. 4a). We will now examine a simplified prediction of what the change in cyclone LWP might look like in response to a uniform warming. ~~As discussed above, it is likely that in a warming world the change in cyclone vorticity, and thus wind speed will be relatively slight.~~ If we assume that the distribution of wind speed remains unchanged, that frequency of occurrence of cyclones remains unchanged, and that WVP increases by 6%/K due to increasing SST(Fig. 3~~Fig. 3~~c) we can estimate the change in WCB moisture flux ~~in the NH (0.22 mm/day, Fig. S7) and SH (0.20 mm/day Fig. S8)~~ consistent with a uniform 1K warming (Fig. 6~~6~~). In this paper we have been utilizing a linear fit between WCB moisture flux and cyclone LWP. As can be seen in Fig. 6~~6~~a the shape of the relationship between WCB moisture flux and cyclone LWP is better represented by an exponential fit (as in McCoy et al. (2018b)). However, the variance in LWP explained by either function is nearly identical. ~~Assuming that the~~The linear relationship between WCB moisture flux and -LWP_{CM} ~~relationship remains unchanged in a warmed climate this new distribution of WCB moisture flux would yield~~predicts an increase of ~~3.42 g/m² in LWP in the NH and a~~ 3.6~~7~~2 ~~1~~ g/m² ~~increase~~ in the SH (Fig. 6d) in response to the change in WCB moisture flux shown in Fig. 6~~6~~c. If the exponential fit is used the change in cyclone LWP is 3.71 g/m^2. Thus, use of a linear relationship between WCB moisture flux and LWP may slightly under-estimate the change in cylone LWP to warming.

Does this prediction offer any more information than an analysis using SST alone? The dependence of LWP_{CM} on SST_{CM} in the SH is shown in Fig. 66b. The relationship appears to be somewhat non-monotonic (LWP increases with SST until 10°C and then decreases) and the correlation is substantially weaker than between WCB moisture flux and LWP_{CM}. Linear regression of LWP_{CM} on SST_{CM} and a 1K increase in SST_{CM} predicts a 1.12 g/m^2 increase in LWP_{CM}, nearly a third of the prediction based on changes in WCB moisture flux. (Fig. S7 and Fig. S8). We offer this quick estimate in order to provide an approximate scale to the potential of the WVP-mediated changes in extratropical cyclone LWP in a warming climate. An estimate of the change in reflectivity consistent with this change in cyclone LWP will be offered belowin section 3.4 when we examine the change in cyclone structure in response to change in WCB moisture flux. In the following section we will investigate whether WCB moisture flux-driven increases in LWP can explain the warming response in GCMs.

Comparison of the trend in Southern Ocean LWP_{RM} for the models listed in Table 2 are shown in Fig. 7b. Despite the models being run in AMIP-mode with prescribed SSTs, there is significant variability in the trend in LWP_{RM} in the period 1992-2015 (note that CFMIP2 models simulated 1979-2008). The GCMs all show a positive trend that is significant at 95% confidence, but generally under-predict the strength of the trend. It is also interesting to note that the trend in LWP_{RM} across the Southern Ocean is almost completely explained by WCB moisture flux variability in all the GCMs. In the following section we will revisit this puzzle and use spatial variability within cyclone composites and cloud top phase to attempt to disentangle the contributions of ice-to-liquid transitions and WCB moisture flux.

3.3.4 Predicting the cyclone LWP response in transient warming simulations

In section 3.3.1 and 3.3.2 we examined month-to-month regional variability. In section 3.3.3 we examined whether trends in SST, WCB moisture flux, and cyclone LWP from 1992-2015 were consistent with the predictions based on month-to-month variability. The analysis in these sections inferred that increasing WCB moisture flux should increase cyclone LWP in a warming world. In this section we will As discussed above, it is likely that in a warming world the change in cyclone vorticity, and thus wind speed will be relatively slight. If we assume that the distribution of wind speed remains unchanged, that frequency of occurrence of cyclones remains unchanged, and that WVP increases by 6%/K (Fig. 6c) we can estimate the change in WCB moisture flux in the NH (0.22 mm/day, Fig. S7) and SH (0.20 mm/day Fig. S8) consistent with a uniform 1K warming. Assuming that the WCB-LWP_{CM} relationship remains unchanged in a warmed climate this new distribution of WCB moisture flux would yield an increase of 3.42 g/m^2 in LWP in the NH and a 3.71 g/m^2 increase in the SH (Fig. S7 and Fig. S8). We offer this estimate in order to provide an approximate scale to the potential of the WVP-mediated changes in extratropical cyclone LWP in a warming climate. An estimate of the change in reflectivity consistent with this change in cyclone LWP will be offered below.

Comparison of the trend in Southern Ocean LWP_{RM} for the models listed in Table 2 are shown in Fig. 7b. Despite the models being run in AMIP-mode with prescribed SSTs, there is significant variability in the trend in LWP_{RM} in the period

1992-2015 (note that CFMIP2 models simulated 1979-2008). The GCMs all show a positive trend that is significant at 95% confidence, but generally under-predict the strength of the trend. It is also interesting to note that the trend in LWP_{RM} across the Southern Ocean is almost completely explained by WCB moisture flux variability in all the GCMs. In the following section we will revisit this puzzle and use spatial variability within cyclone composites and cloud top phase to attempt to disentangle the contributions of ice-to-liquid transitions and WCB moisture flux.

As mentioned above, this analysis relies ontest the assumption that the relationship between WCB moisture flux and LWP is invariant under warmingcan predict the warming response of a model. At the time of writing the only GCMs considered in this study that have simulated a global increase in temperature (outside of the observational record) are the GCMs participating in CFMIP2 (see Table 2Table 2). The CFMIP2 GCMs performed a set of simulations where the specified SST in the atmosphere-only (AMIP) runs was increased by 4K (AMIP+4K). The CFMIP2 GCMs represent a wide array of different relationships between WCB moisture flux and cyclone LWP and it is hoped that even though we have limited our analysis of cyclone behavior in a warmed climate to these models, it still provides insight into the broader collection of models examined in the rest of this study.

Comparison of the WCB moisture flux-LWP relationship (see Fig. 1Fig. 1) between the AMIP and AMIP+4K CFMIP2 simulations shows that they are fairly similar in the SH (Fig. 7Fig. 7). Only IPSL-CM5A-LR has a substantially different relationship between LWP_{CM} and WCB moisture flux in the AMIP and AMIP+4K simulations. Examination of the NH shows that all the models display a downward shift in the WCB moisture flux-LWP relationship in the warmed simulations (Fig. S9S10). It is unclear why the WCB moisture flux-LWP relationship in the NH shifts downward, while it shifts upward in the SH in only one of the GCMs. At least in the SH this upward shift is conceptually consistent with a decrease in precipitation efficiency due to decreased ice-phase precipitation. In this case an increase in cyclone LWP would be in line with the necessity of balancing precipitation out of the cyclone and moisture flux into the cyclone(McCoy et al., 2018b).

Changes in extratropical cyclones in a warming climate may affect the relationship between WCB moisture flux and LWP. However, moisture flux changes still explain most of the difference in cyclone LWP between the AMIP and AMIP+4K simulations examined here. To test whether the current climate's variability can be used to predict the future (as in Qu et al. (2015)) we train For each GCM a linear regression model of the form $LWP_{CM} = a \cdot WCB + c + residb$ for each GCM. The regression model is fit using the variability in the present-day AMIP simulations. Regression models are trained independently in each hemisphere. Cyclone LWP in the AMIP+4K simulations is predicted based on the regression model and the WCB moisture flux in the AMIP+4K simulations. That is to sayTo reiterate, if we know the relationship between moisture flux and cyclone LWP in the current climate, and we know how moisture flux changes, then can we predict the change in cyclone LWP?

Changes in WCB moisture flux explain the majority of cyclone LWP difference between the AMIP+4K and AMIP simulations (Fig. 88Fig. S10). Over 80% of the difference in southern hemisphere cyclone LWP between AMIP and AMIP+4K is explained by differences in WCB moisture flux in four out of five of the models. The change in cyclone LWP in IPSL-CM5A-LR is 30% greater than the change predicted by WCB moisture flux alone, consistent with a potential phase-transition-driven increase in LWP. For completeness the same calculation was carried out in the NH. Differences in northern hemisphere cyclone LWP between AMIP and AMIP+4K are within 25% of the prediction based on the AMIP WCB moisture flux-LWP relationship and the difference in WCB moisture flux (Fig. ~~S11~~S11).

The ability of the regression model to explain changes in LWP is quite high, although its ability to explain monthly- and regional-mean variability is not exceptionally high in some of the GCMs (Fig. S8). As discussed in section 3.3.1, the residual term in Eq. 4 is generated by predictors not considered in our analysis. For example, cloud droplet number concentration(CDNC), which has been shown to have substantial predictive ability(McCoy et al., 2018b). These unconsidered predictors might contribute to the variance in the current climate, leading to a lower explained variance by the regression model, but if these other predictors do not change between the AMIP and AMIP+4K simulations then the regression model will be able to accurately predict the change in LWP between these simulations. For example, aerosol emissions do not change between AMIP and AMIP+4K. By extension CDNC is unlikely to change so variance unexplained by this factor in the historical climate is unimportant for explaining the change in LWP between AMIP and AMIP+4K.

It appears that the relationship between extratropical cyclone latitude and wind speed and SST and cyclone WVP from the current climate hold in a warmed climate.

~~Changes in WCB moisture flux dominate the change in Southern Ocean cyclone LWP in the CFMIP2 models between AMIP and AMIP+4K. We also examine changes in the components of WCB moisture flux: WVP and wind speed. The change between AMIP and AMIP+4K agrees with the sensitivity inferred from the interannual variability (Fig. 3bc). As cyclones~~As cyclones shift poleward in response to warming their mean wind speed increases (Fig. 9~~9~~). Similarly~~,~~ ~~and~~ as SSTs rise WVP increases ~~(Fig. S12)~~. As prescribed by the AMIP+4K simulations the SST rises in both hemispheres, leading to increasing WVP. The response in mean cyclone position is varied and difficult to interpret in the context of a green house gas-induced warming due to the fixed SST imposed in these simulations. ~~However, it does appear that the relationship between inter-annual anomalies in average extratropical cyclone latitude and wind speed from the current climate holds in a warmed climate.~~ The mechanism that links the mean cyclone latitude and cyclone wind speed is not clear, but one possibility is that cyclone lifecycle changes in response to warming, leading to changes in the average wind speed within a cyclone as the average latitude range that cyclones exist in changes. We reserve understanding why mean cyclone location and wind speed change in this way for a future paper using both uniform increases in SST and a more realistic warming pattern.

In summary, we find that most of the cyclone LWP trend in the SH observational record can be explained by a steady increase in WCB moisture flux, as opposed to a transition to less-glaciated clouds. We support this result by contrasting CFMIP2 AMIP and AMIP+4K simulations. More than ~~70~~80% of the difference in SH cyclone LWP between these simulations can be explained by changes in WCB moisture flux. In the next section we will utilize observations of cloud-top phase to further examine how cloud glaciation might affect cyclone LWP.

3.4 ~~Changes in~~The spatial distribution of LWP ~~and cloud-top phase~~within cyclones

3.4.1 Sensitivity to WCB moisture flux and SST

In ~~the preceding sections~~section 3.3 we have investigated the link between large-scale meteorology, as characterized by WCB moisture flux, and extratropical cyclone LWP averaged to a cyclone-mean, or regional scale. The moisture flux along the WCB explains a great deal of the variability in cyclone LWP in models and observations. ~~and that~~Increases in WCB moisture flux also predict the decadal trend in SH LWP_{RM} ~~seems to be largely related to WCB moisture flux~~. Over 80% of the cyclone LWP response in the SH can be explained using the GCM's current variability and the predicted change in WCB moisture flux. All of these lines of evidence show that mixed-phase transitions do not account for the majority of the increase in LWP in response to warming, and ultimately the negative feedback in extratropical cyclones. ~~Here~~ In this section we will use observations of cloud-top phase to examine whether any variability in extratropical cyclone LWP can be linked to a transition from ice to liquid consistent with a warming signal (that is to say, phase transitions consistent with the mixed-phase cloud feedback).

~~As noted above, WVP depends on SST via Clausius-Clapeyron, making it difficult to empirically disentangle SST-driven ice-to-liquid transitions from moisture flux driven variability. Here~~ W~~w~~e will examine the response of LWP within the cyclone composite (LWP_{ij}) based on multiple linear regression on WCB moisture flux into the cyclone and SST_{ij}. Similarly to Eq. 4, t~~T~~he regression model considered here is

$$LWP_{ij} = a_{ij} \cdot WCB + b_{ij} \cdot SST_{ij} + c_{ij} + resid_{ij} \qquad [6]$$

where the subscripts i and j refer to areal averages within the composites in the longitudinal and poleward directions (see Table 1~~Table 1~~). Each averaging region is approximately 200 kmx200 km. Values for the coefficients are calculated by fitting the regression model across cyclones in each averaging region *ij*. To simplify our presentation and compare across GCMs and observations, we show the regression coefficients for the GCMs in Table 2~~Table 2~~ and the observations averaged in the longitudinal direction. The zonal-means of coefficient values of a_{ij} and b_{ij} are shown in Fig. 10 (full composite maps of a_{ij} and b_{ij} are shown in Fig. S12, but show little additional structure in the longitudinal direction)~~Fig. 9~~. Unsurprisingly, there is a strong positive relationship between WCB moisture flux and LWP_{ij} throughout the cyclone (e.g. the coefficient a_{ij} in Eq. 6). Increasing SST_{ij} tends to covary with increased LWP_{ij} in the part of the composite poleward of the low and with decreased LWP_{ij} in the portion of the composite equatorward of the low (e.g. b_{ij}).

~~Most of the variability in the sensitivity of LWP_{ij} to SST_{ij} is in the latitudinal direction, while sensitivity to WCB peaks near the origin. To simplify our presentation and compare across GCMs and observations, we show the regression coefficients for the GCMs in Table 2 and the observations averaged in the longitudinal direction (Fig. 10).~~ Comparison between models and observations show that there is variability between models and observations regarding the sensitivity of LWP_{ij} to WCB moisture flux into the cyclone ~~(ac)~~(Fig. 10~~10~~a), which is consistent with the range of slopes shown in Fig. 1~~Fig. 1a~~. However, the relation between LWP_{ij} and SST_{ij} within the composite is fairly similar across models ~~(bd)~~(Fig. 10~~10~~b).

Increasing SST in the equatorward part of the composite tends to covary with decreasing LWP_{ij} and increasing SST_{ij} in the poleward part of the composite covaries with increases in LWP_{ij}.

This negative relationship between local changes in SST_{ij} and LWP_{ij} within the part of the composite that is equatorward of the low agrees with previous studies showing break up in midlatitude stratocumulus with advection over warmer SSTs due to decoupling of the subcloud layer (Norris and Iacobellis, 2005), and is consistent with the prevailing hypothesis regarding warm clouds in the sub-tropical trade cumulus and stratocumulus regions (Klein et al., 2017). It is possible that the poleward enhancement in LWP_{ij} in response to enhancement in SST_{ij} may relate to shifts from ice to liquid cloud, but it might also relate to other meteorological controls on cloud cover and thickness(Grise and Medeiros, 2016).

Do the changes in LWP inferred from ~~Fig. 9~~Eq. 6 translate into a meaningful change in reflected shortwave radiation? As shown in Bodas-Salcedo (2018) and Bodas-Salcedo et al. (2016), the effect of changes in LWP are highly dependent on the cloud regime that they are occurring in. In particular, overlying cloud can act to blunt the effect of changes in LWP on top of atmosphere ~~radiation~~reflected shortwave radiation. For example, an optically thick layer of ice cloud over the liquid in the cyclone would result in very little impact from LWP variability. ~~Do the changes in LWP inferred from Fig. 9 translate into a meaningful change in reflected shortwave?~~ We offer an approximate calculation of the change in reflected shortwave radition consistent with the coefficients calculated in ~~Fig. 9cd~~Eq. 6 using observations from CERES. The idea underlying this calculation is that the CERES top of atmosphere reflected shortwave radiation will ~~to account~~ include ~~for~~ the effects of ~~masking by~~ overlying ice cloud. The sensitivity in reflected shortwave radiation to LWP will be lowered by the effects of ice cloud. Daily-mean all-sky albedo from CERES SYN1DEG(Doelling et al., 2016;Wielicki et al., 1996) was ~~created~~ calculated from 3-hourly data from 2003-2015 where the solar zenith angle does not exceed 45° (see McCoy et al. (2018b) for a full discussion of th~~ese~~is data). Regression of albedo on LWP variability gives an empirical relationship between LWP and albedo (Fig. ~~S13~~S14). Radiative fluxes are more readily comparable to previous studies of cloud feedbacks. Thus, the change in albedo is scaled by the annual mean insolation taken from the CERES EBAF-TOA edition 4 dataset (Loeb et al., 2009) averaged over 30-80° to give the change in Wm^{-2} per change in LWP. While empirical, this is a relatively simple way to examine the effects of ~~cloud masking~~overlying ice cloud blunting the effects of underlying liquid variability on top of atmosphere albedo.

We find that LWP is always positively correlated with albedo (Fig. ~~S13~~S14). At zeroth order we expect this based on the robust positive relationship between cloud fraction and all-sky albedo(Bender et al., 2011a;Bender et al., 2017), and remembering that microwave LWP is the average of in-cloud liquid and clear sky. If we multiply the relationships for the SH ~~shown in cd~~ from the regression model (Eq. 6, Fig. S12ab) by the slope of the regression between LWP and albedo, then this gives the change in albedo across the cyclone composite consistent ~~with Eq. 6 and~~ a unit increase in WCB moisture flux or SST. WCB moisture flux increases by approximately 0.2 mm/day for a 1K increase in SST in the SH if wind speed is held constant and WVP increases following Clausius-Clapeyron (Fig. 6~~6c~~~~Fig. S8~~). Thus, we scale the change in albedo per unit change in WCB moisture flux by 0.2 mm/day to give a change in albedo related to changes in WCB moisture flux consistent with a 1K SST increase (assuming no change in wind speed). In the context of Eq. 6 the net change in reflected shortwave that is implied by a 0.2 mm/day increase in WCB moisture flux is 0.87 Wm^{-2} and reflected shortwave decreases by 0.23 Wm^{-2} for a 1K SST increase ~~(Fig. S14)~~. Again, these empirical calculations are simplistic and are only intended to approximate the effect of ~~cloud masking~~the blunting of the efficacy of liquid on driving changes in top of atmosphere albedo~~, which has been identified as a key factor in cloud feedbacks in midlatitude cyclones(Bodas-Salcedo, 2018)~~. ~~A more precise estimate of changes in cyclone albedo accounting for cloud masking is reserved for future work.~~ Overall, we find that the changes in LWP that are empirically linked to changes in WCB moisture flux and SST in the multiple regression shown in Eq. 6 translate to ~~reasonably~~ reasonably large negative and positive feedbacks, respectively~~, providing that the current relationship between LWP and albedo within cyclones holds in a warming world~~. These implied feedbacks may be contrasted with the zonal-mean cloud feedbacks from the CFMIP2 and CFMIP1 models, with a strongest value for the negative lobe of the shortwave cloud feedback dipole of -2 Wm^{-2} in some GCMs (Zelinka et al., 2013;Zelinka et al., 2016).

3.4.2 Insight from cloud-phase observed by AIRS

We have shown that LWP ~~changes~~ covaries with WCB~~associated with changes in SST and~~ moisture flux at a fixed SST ~~have~~ and how SST and LWP covary at a fixed WCB moisture flux within cyclones. It is also shown that the LWP changes associated with changes in SST and moisture flux could have the capability to appreciably change reflected shortwave flux in extratropical cyclones. Is this increase in LWP_{ij} with increasing SST_{ij} at a fixed WCB moisture flux in the poleward half of the composite from phase transitions? We examine the sensitivity of cloud top phase to SST_{ij} and WCB to see if there is any consistency in regions where clouds become more liquid dominated, and regions where the LWP_{ij} sensitivity to SST_{ij} suggests a phase transition. Cloud top phase is measured by the AIRS instrument during the period 2003-2015. It is important to caveat the following analysis by noting that, unlike the other observational data sets used in this paper (MAC-LWP, and CERES), data from AIRS is not diurnally-averaged. It is only available for the Aqua satellite's overpass times. The effects of this temporal subsetting of the data are not clear. However, the goal of the analysis we are pursuing is qualitative. Our intention is to see if liquid cloud phase increases at the expense of ice phase with increasing SST in the same regions that LWP increases with increasing SST. Fig. S15 shows cyclone composited AIRS observations. The structure of ice and liquid phase exhibits a reasonable ice cloud shield and liquid warm sector- indicating that it may shed at least some light on variability in cloud-top phase within cyclones.

-As discussed in the methods section, when the cloud is broken, mixed-phased, or possibly supercooled liquid the infrared signature becomes weak and the cloud top is flagged as unknown by AIRS. Here, we examine the probability that a given cloud-top phase (liquid, ice, or unknown) was detected by AIRS given that any phase detection was made in a cyclone composite framework. ~~(Fig. 11). We perform the same analysis on the probability of a cloud top being flagged as liquid, ice, or unknown as performed on LWP.~~ We examine how phase depends on WCB moisture flux, and how it depends on SST_{ij}. This is done analogously to the analysis performed ~~above~~ in section 3.4.1 in the context of multiple linear regression

$$p(x)_{ij} = a_{ij} \cdot WCB + b_{ij} \cdot SST_{ij} + c_{ij} + resid_{ij} \quad [6]$$

where $p(x)_{ij}$ is the probability of a cloud top phase being an arbitrary phase *x* (ice, liquid, or unknown) given that a phase detection was made. ~~The coefficients from performing this regression across cyclones in the SH and NH are shown in Fig. 12. Overall, the effect of increasing moisture flux into the cyclone is to increase the frontal cloud which is ice-topped (Fig.~~

12c and Fig. 12c). The ice cloud is anti-correlated with SST- as one would intuitively expect (Fig. 11d and Fig. 12d). However, most of this is along the comma-shaped frontal region, consistent with Bodas-Salcedo (2018).In the SH increasing SSTs covaries with enhancement in the prevalence of unknown cloud tops at the expense of liquid and ice fraction across the entire cyclone composite (Fig. 12bdf).

In this work we have focused on the SH for brevity because it is interesting from a modelling perspective and because the behavior of cyclone LWP as a function of WCB moisture flux in the NH is approximately the same, giving little additional explanatory value to including it. However, the preponderance of unknown-topped cloud observed by AIRS in the SH necessitates contrasting NH and SH midlatitude oceans to offer insight into whether cloud top phase changes might explain some of the response of LWP to SST within cyclones.

The coefficients from training Eq. 6 across cyclones in the SH are shown in Fig. 12. Overall, the effect of increasing moisture flux into the cyclone is to increase the frontal cloud which is ice-topped (Fig. 12c). The ice cloud is anti-correlated with SST- as one would intuitively expect (Fig. 11d and Fig. 12d). However, most of this is along the comma-shaped frontal region, consistent with Bodas-Salcedo (2018). In the SH increasing SSTs covaries with enhancement in the prevalence of unknown cloud tops at the expense of liquid and ice fraction across the entire cyclone composite (Fig. 12bdf).

While the SST-dependence of LWP_{ij} is quite similar across models and observations in both hemispheres (b(Fig. 1010b, Fig. S14d), the dependence of observed cloud-top phase on SST_{ij} is very different in the NH and SH. This because AIRS identifies a very large fraction of the SH clouds as unknown phase.

In the NH, the probability of liquid-topped clouds increases with increasing SST in the poleward part of the composite (Fig. 11Fig. 11b). Toward the equator, increasing SST increases the fraction of unknown cloud tops (Fig. 11Fig. 11f). In the SH increasing SSTs covaries with enhancement in the prevalence of unknown cloud tops at the expense of liquid and ice fraction across the entire cyclone composite (Fig. 13bdf).

Increasing liquid fraction in the poleward half of NH cyclones over warmer SSTs (Fig. 11Fig. 11b) is consistent with transitions from a more ice-dominated to a more liquid-dominated state. The covariance of LWP_{ij} and SST_{ij} in these regions (bFig. 1010b, Fig. S12bd,13b)) appears to bear out this explanation. This may simply reflect an increase in liquid at the expense of ice, or it may reflect an increase in overall condensate via suppression of the efficient depletion of cloud condensate via ice-phase precipitation(Field and Heymsfield, 2015).

The decrease in both liquid and ice fraction and the increase in unknown cloud tops over warmer SSTs in equatorward portion of NH cyclones and in the entirety of SH cyclone composites is perplexing. One possibility is that I it may be linked to transitions from closed to open mesoscale cellular convection(McCoy et al., 2017c;Norris and Iacobellis, 2005) leading to weaker IR signals and thus unknown cloud top-phase classification from AIRS (Nasiri and Kahn, 2008;Kahn et al., 2011). This may point toward the pathway: higher SST, more cumuliform cloud, and more broken cloud(Norris and Iacobellis, 2005), which is also consistent with other empirical studies of low cloud cover in the subtropics(Klein et al., 2017). It is unclear why this behavior only takes place in the equatorward parts of NH cyclones, while it occurs across the entire cyclone composite in the SH. OneAnother possibility is that the Southern Oceans are much more dominated by supercooled liquid cloud(Chubb et al., 2013;Kanitz et al., 2011;Hu et al., 2010;Tan et al., 2014) and they do not have the same phase transition sensitivity as the NH oceans. This seems consistent with the lower sensitivity of poleward LWP within SH cyclones to local SST_{ij} (bd). Overall, the magnitude of the decrease in liquid-topped clouds with increased SST_{ij} is relatively slight in SH. The magnitude of the increase in unknown tops with increasing SST_{ij} in the SH is relatively similar to magnitude of the increase in liquid-topped clouds in the NH. Finally, the decrease in ice-topped cloud across the cyclones in both NH and SH is fairly similar with an ~0.075%/K decrease implied by covariability in both (Fig. S15b). A higher proportion of supercooled liquid phase clouds in the SH is also consistent with an increasingly ambiguous spectral signature in the mid-infrared window region as the index of refraction for supercooled liquid is known to be temperature-dependent (Rowe et al., 2013) and is not accounted for in the current AIRS thermodynamic phase algorithm.

To summarize, we investigate the possibility that an ice to liquid transition consistent with the mixed-phase feedback proposed in other studies may account for LWP trends unrelated to trends in WVP, which are ultimately driven by Clausius-Clapeyron and increasing SST. Disentangling contributions from moisture flux and phase transitions is a difficult problem because WVP, SST, and WCB moisture flux covary. We leverage the cloud-top phase retrievals from AIRS and the geographic distribution of variability within the cyclone composite to try and detach variability associated with moisture flux from variability associated with phase transitions. A great deal of the inter-model variability appears to be owing to variability in the portrayal of the WCB moisture flux-LWP relationship, and it is found that models and observations are in surprisingly good agreement regarding the covariability of LWP_{ij} to SST_{ij} in the context of a multiple linear regression of LWP_{ij} on WCB and SST_{ij}(Fig. 10). There is an increase in LWP_{ij} with increasing SST_{ij} in the poleward part of the cyclone that is spatially consistent with the region where SST_{ij} and liquid-topped cloud fraction are positively correlated in the NH. This is supportive of this sensitivity of LWP_{ij} to SST_{ij} being linked to phase transitions. Ultimately, the cancellation of a positive covariability between SST_{ij} and LWP_{ij} in the poleward region of the cyclone and a negative covariability in the equatorward regions leads to an overall slight negative covariability between SST_{CM} and LWP_{CM} is considered (Fig. 7).

Unfortunately, many of the cloud tops in the Southern Ocean cannot be confidently classified as either liquid or ice by AIRS (Thompson et al., 2018). This makes it difficult to establish whether cyclones are transitioning to a more liquid-dominated state. In the SH, increasing SST covaries with increasing unknown phase identifications. One possibility is that increasing SST alters the mesoscale cellular convection leading to open cells(McCoy et al., 2017c;Norris and Iacobellis, 2005), which AIRS cannot identify. Another possibility is that the SH ocean is dominated by supercooled liquid cloud, and thus does not become any more liquid with warming(Hu et al., 2010). This corresponds to decreasing LWP with increasing SST in both observations and models. This may point toward the pathway: higher SST, more cumuliform cloud, and more broken cloud(Norris and Iacobellis, 2005), which is also consistent with other empirical studies of low cloud cover in the subtropics(Klein et al., 2017). Further clarity in the cloud phase information from AIRS may require additional algorithm development to exploit hyperspectral infrared radiances to classify supercooled liquid and mixed phase spectral signatures (e.g., Kahn et al. (2011); Rowe et al. (2013)), including the impacts of sub-pixel horizontal variations of liquid and ice phase mixtures (e.g., Thompson et al. (2018)).

4 Conclusions

We have examined the behavior of extratropical cyclones (centered 30°-80°) in models and long-term microwave observations for the period 1992-2015. (Zelinka et al., 2012b)(Trenberth and Fasullo, 2010)The central tool used in this study is the ability toWe use the characterize cyclones by their meteorology using the warm conveyor belt (WCB) moisture flux to characterize the synoptic state of these cyclones. The WCB moisture flux is the product of water vapor path (WVP) and wind speed at 10 meters (WS_{10m}) averaged within 2000 km of the cyclone center. AsAs the moisture flux along the WCB increases the liquid water path (LWP) within the cyclone increases . We find that the WCB moisture flux explains 28-42% of anomalous monthly, regional variability in LWP across different ocean basins (Fig. 1, Fig. 2Fig. 2a).

This relationship between the synoptic state, as characterized by WCB moisture flux, and the cyclone LWP appears across observations and models. The ability of GCMs to reproduce this relationship is examined using an array of models from high-resolution simulations within the convective grey zone to coarse resolutions typical of fully-coupled GCMs performing climate integrations. It is found that all the models considered here reproduce the dependence of LWP on moisture flux, but theirthe sensitivities sensitivity of cyclone LWP to WCB moisture flux in these GCMs vary varies by a factor of two around the observed sensitivity. There did not appear to be awas not a strong, systematic dependence of this relationship on resolution on resolution (Fig. 1Fig. 1). However, convection-permitting models agreed well with each other and the observations-indicating Overall, we suggest that this relationship between moisture flux and LWP within cyclones should be used in the evaluation of the physicality of GCMs. Further, we find that simulations that do not include a convective parameterization (NICAM, ICON, and UM-CASIM) tend to have much more similar relationships between WCB moisture flux and cyclone LWP, indicating that parametric uncertainty within convective parameterizations may contribute to uncertainty in this the relationship between WCB moisture flux and cyclone LWP across in GCMs.

WCB moisture flux into cyclones will increase as the planet warms because WVP scales with temperature following Clausius-Clapeyron. Because cyclone LWP increases with WCB moisture flux this is projected to lead to a negative shortwave cloud feedback. A simple calculation holding wind speed and cyclone frequency of occurrence fixed and assuming that WVP changes by 6% estimates an increase in cyclone LWP of 3.62 g/m^2 in the SH (Fig. 66). An empirical calculation of brightening estimates that changes in cyclone LWP due to enhanced WCB moisture flux would equate to a brightening of 0.87 Wm^{-2} within Southern Ocean cyclones, which is an appreciable fraction of the multimodel mean shortwave cloud feedback(McCoy et al., 2016;Zelinka et al., 2013).

We find that there is support for a negative feedback described above by examining decadal trends in LWP within Southern Ocean cyclones (Fig. 4). Most of the observed trend over the period 1992-2015 can be explained by increased WCB moisture flux, which is primarily driven by increasing WVP.(Liu and Curry, 2010) Within the observational record we can only infer feedbacks from covariability, but by using model simulations of transient warming we can see if these inferences have predictive ability. Further, we find that aAnalysis of simulations performed with observed SSTs and SST enhanced by 4K show that differences in WCB moisture flux can explain the majority of the change in simulated cyclone LWP between the current climate and the warmed climate (Fig. 88Fig. S10,11). Thus,This supports the idea that our theunderstanding of the relationship between WCB moisture flux and cyclone LWP in the current climate may be used to understand cloud feedbacks. (Caldwell et al., 2016)

Based on this

Variability in WCB moisture flux appears to drive variability in midlatitude cyclone LWP. What in turn drives variability in WCB moisture flux? The WCB moisture flux is the product of water vapor path (WVP) and wind speed at 10 meters (WS_{10m}) averaged within the cyclone. WVP is strongly coupled to SST via Clausius-Clapeyron, and WS_{10m} enhances in cyclones as they move poleward through their life cycle (Fig. 2bc). This feature exists in both observations and models (Fig. 3bc). These relationships also hold in the CFMIP2 models when SSTs are increased by 4K (AMIP+4K) (Fig. S12). wWe propose two extratropical cloud feedbacks within cyclone systems:

1. a A Clausius-Clapeyron mediated local feedback where increasing atmospheric temperature enhances the available moisture to be fluxed into the cyclone. This feedback is in line with the feedback proposed in Betts and Harshvardhan (1987), but expressed in the framework of a midlatitude cyclone, which imposes a structure on the derivative of the moist adiabat with respect to temperature., and a
2. A dynamical feedback related to shifts in the storm track and changes in cyclone developmentchanges in the genesis and development of cyclones in response to warming, which in turn affects the wind speed and thus the flux of moisture into the cyclone. The former feedback is in line with the feedback proposed in Betts and Harshvardhan (1987), but expressed in the framework of a midlatitude cyclone, which imposes a structure on the derivative of the moist adiabat with respect to temperature. The sign of the wind speed-driven feedback appears to be uncertain in a warming climate, but. Between the CFMIP2 AMIP and AMIP+4K simulations the midlatitude cyclones shifted poleward and equatorward in different models (Fig. S12), but the relationship between latitude and wind speed between AMIP and AMIP+4K mirrored the relationship inferred by variability within AMIP. tThis relationship creates a pathway between synoptic-scale dynamics and the cloud feedback.

Cloud-top phase observed by AIRS was used to investigate whether changes in LWP within cyclones unexplained by WCB moisture flux were consistent with a transition from ice to liquid phase.A simple calculation holding wind speed and cyclone frequency of occurrence fixed and assuming that WVP changes by 6% estimates an increase in cyclone LWP of 3.42 g/m^2 in the NH and 3.71 g/m^2 in the SH (Fig. S7 and Fig. S8). An empirical calculation of brightening estimates that this would equate to a brightening of 0.87 Wm^{-2} within Southern Ocean cyclones (Fig. S14), which is an appreciable fraction of the overall shortwave cloud feedback(McCoy et al., 2016;Zelinka et al., 2013).

We find that there is support for a negative feedback described above by examining decadal trends in LWP within Southern Ocean cyclones (Fig. 7). Most of the observed trend over the period 1992-2015 can be explained by increased WCB moisture flux, which is primarily driven by increasing WVP. Further, we find that analysis of simulations performed with observed SSTs enhanced by 4K show that differences in WCB moisture flux can explain the majority of the change in simulated cyclone LWP between the current climate and the warmed climate (Fig. S10,11). This supports the idea that our understanding of the relationship between WCB moisture flux and cyclone LWP in the current climate may be used to understand cloud feedbacks.

The majority of observed and modeled trends in SH cyclone LWP in the current climate can be explained by changes in WCB moisture flux. Similarly, the majority of the simulated change in cyclone LWP between the current climate and a warmed climate can be explained by changes in WCB moisture flux. Do changes in cloud phase play a role in altering LWP within extratropical cyclones? While changes in WCB moisture flux explain a great deal of LWP variance within cyclones, there is a residual signal in LWP related to SST leading to increased LWP in the poleward half of the composite (bd). In the half of the composite that is eequatorward half of cyclones of the low the LWP decreases with increasing SST, in keeping with previous studies(Norris and Iacobellis, 2005) and in the poleward half of cyclones LWP increases with increasing SST. Utilizing cloud top phase data from AIRS we show that changes from ice to liquid cloud could contribute to increasing LWP with increasing SST in the poleward half of the cyclone composites (Fig. 11Fig. 11b and Fig. 12Fig. 12b). In the equatorward part half of NH the cyclone composites and across all of SH cyclones unknown phase (broken or mixed-phase) cloud tops become more frequent as SST increases increases across the NH (Fig. 11Fig. 11f). In the SH unknown phase cloud tops increase at the expense of liquid and ice in all parts of the composite (Fig. 12f, and Fig. S15b). This may be consistent with breakup of stratocumulus over warmer SSTs(Norris and Iacobellis, 2005).

In summary, we find a robust relationship between the moisture flux into extratropical cyclones and their LWP in observations and GCMs (McCoy et al., 2018b)(Fig. 3Fig. 3a). This relationship has the ability to explain cyclone-to-cyclone variability, regional- and monthly-mean variability across ocean basins (Fig. 2Fig. 2a), and the observed trend in Southern Ocean LWP from 1992 to 2015 (Fig. 4Fig. 4). While we can only examine covariability within the observational record, we can examine the transient climate response within GCMs to see if this relationship has utility in predicting the response of extratropical cyclone LWP to climate change. It is found that over 80% of the LWP change in extratropical cyclones can be explained using their change in WCB moisture flux and the relationship between WCB moisture flux and cyclone LWP in their simulations of the present climate. We propose that the relationship between WCB moisture flux is a key aspect of whether a GCM will have a strongly or weakly negative shortwave cloud feedback in the extratropics and thus acts as a useful constraint on climate sensitivity(Caldwell et al., 2016).

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Data availability

The AIRS version 6 data sets were processed by and obtained from the Goddard Earth Services Data and Information Services Center (http://daac.gsfc.nasa.gov/). The AIRS data used in this study is cited as: AIRS Science Team/Joao Texeira (2013), AIRS/Aqua L2 Support Retrieval (AIRS+AMSU) V006, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed July 2017, doi:10.5067/Aqua/AIRS/DATA207. MERRA2 data was downloaded from the Giovanni data server. CERES data was downloaded through the ceres.larc.nasa.gov ordering interface.

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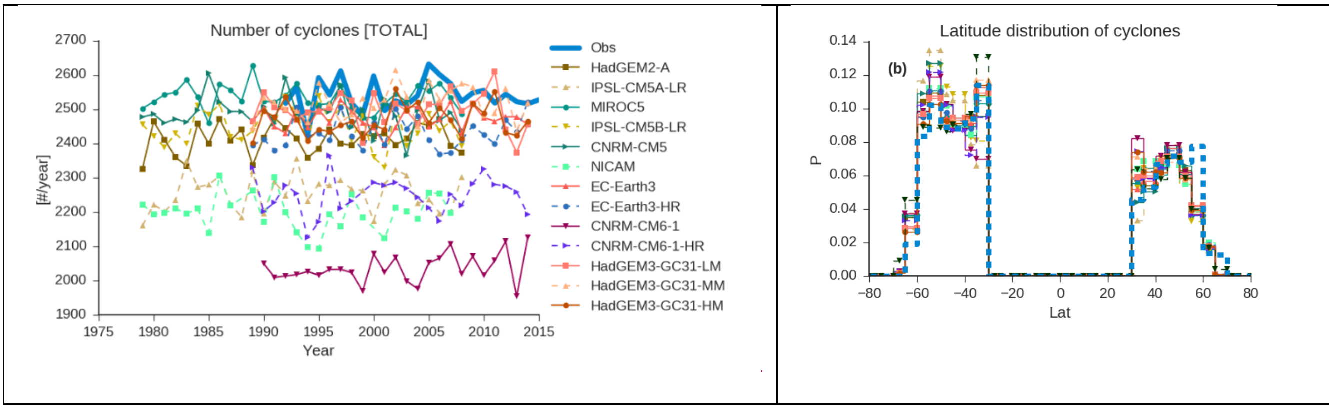
Table 1 Acronyms and subscripts used in this work.

Acronym	Defintion
CCN	Cloud condensation nuclei
CDNC	Cloud droplet number concentration
CM	Cyclone mean within a 2000 km radius of the low pressure center
GCM	Global climate model
LWP	Liquid water path
ij	Mean within each averaging region of the cyclone
NH	Northern hemisphere
RM	Regional mean of individual cyclone means
SH	Southern hemisphere
SLP	Sea level pressure
SO	Southern Ocean
SST	Sea surface temperature
WCB	Warm conveyor belt
WVP	Water vapor path
WS_{10m}	Wind speed at 10 meters

Table 2 Brief descriptions of the models used in this study. The label in the left column is used in some figures for brevity in labelling. The observations used in this study are discussed more completely in the methods section.

Label	Name	Approximate Atmospheric Resolution	References	Time Period
A	Observations	~	See methods	1992-2015
B	HadGEM2-A[1]	1.25°x1.875°~ 139kmx208 km	(Collins et al., 2011;Martin et al., 2011)	1979-2008
C	IPSL-CM5A-LR[1]	1.8947x3.75° ~211kmx417km	(Dufresne et al., 2013)	1979-2008
D	MIROC5[1]	1.4008°x1.40625° ~156kmx156km	(Watanabe et al., 2010)	1979-2008
E	IPSL-CM5B-LR[1]	1.8947°x3.75° ~211kmx417km	(Hourdin et al., 2013)	1979-2008
F	CNRM-CM5[1]	1.4008°x1.40625° 156kmx156km	(Voldoire et al., 2013)	1979-2008
G	NICAM	14km	(Kodama et al., 2015)	1979-2007
H	EC-Earth3[2]	60km	(Haarsma, 2018)	1989-2014
I	EC-Earth3-HR[2]	25km		1989-2014
J	CNRM-CM6-1[2]	150km	(Roehrig, 2018)	1989-2014
K	CNRM-CM6-1-HR[2]	50km		1989-2014
L	HadGEM3-GC31-LM[2]	130km	(Williams et al., 2018)	1989-2014
M	HadGEM3-GC31-MM[2]	60km		1989-2014
N	HadGEM3-GC31-HM[2]	25km		1989-2014
~	ICON	10km	(Giorgetta et al., 2018)	

~	UM-CASIM	0.088°x0.059° 10kmx7km	(McCoy et al., 2018b;Hill et al., 2015)	
	[1]CFMIP2 [2]PRIMAVERA			



~~**Fig. 1 The distribution of daily-mean cyclone centers analyzed in this study. (a) The number of extratropical (30°-80°) cyclone centers identified each year in daily-mean data in the MERRA2 reanalysis and different global models and (b) the latitudinal distribution of cyclone centers. Only cyclone centers over water and where more than 50% of the cyclone center is over ice-free ocean are considered. In (b) the number of cyclone centers identified in each 5° latitude bin is divided by the total number of cyclones. Each cyclone center identified in the daily-mean data is considered independently. SH and NH cyclones are shown combined. In (a) the number of cyclones in a year is rescaled assuming a 365-day year because some of the GCMs have a 360-day year.**~~

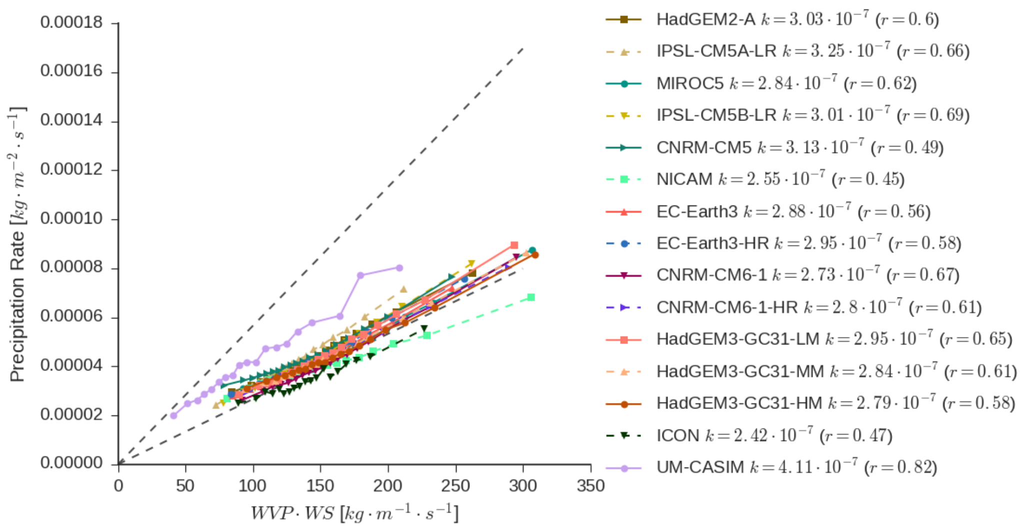


Fig. 2 Cyclone-mean precipitation rate versus WCB moisture flux for the global models examined in this study. The *k* parameter (Field et al., 2011) for each model is noted in the legend along with the correlation between WCB moisture flux and cyclone-mean precipitation rate. The *k* parameter is calculated as the slope of the relationship between the product of WVP and WS_{10m} and the precipitation rate. Dashed lines show the observational bounds on *k* (Field et al., 2011;Naud et al., 2018). For ease of visualization the precipitation rates for each GCM are shown averaged into 19 quantiles of WVP_{CM}*WS_{10mCM}.

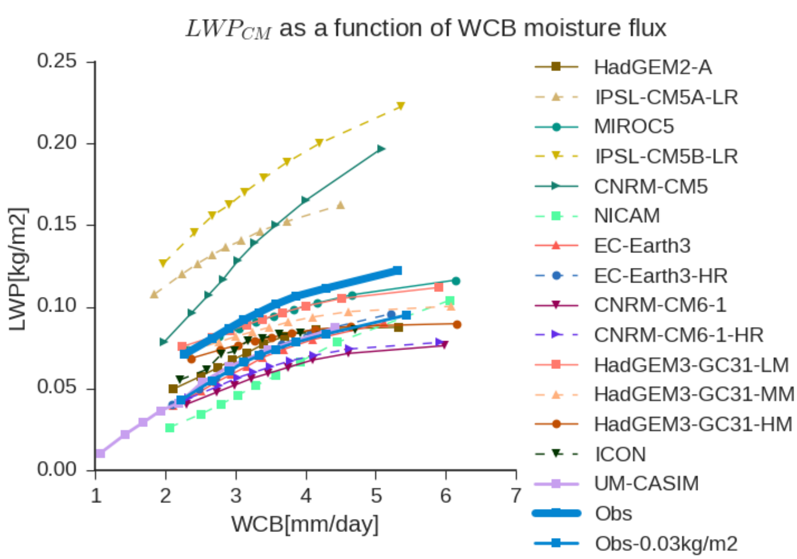


Fig. 1 Cyclone-mean LWP (LWP_{CM}) as a function of WCB moisture flux in models and observations. LWP_{CM} is shown averaged into 9 equal quantiles for the observations and each GCM. The maximum bias in the observations (~0.03kg/m2) is shown as a lighter blue line.

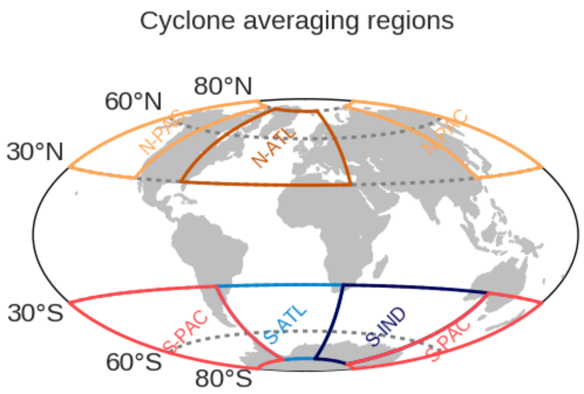


Fig. 4 Averaging regions considered in Fig. 5. Labels refer to the North Pacific (N-PAC), North Atlantic (N-ATL), South Pacific (S-PAC), South Atlantic (S-ATL), and South Indian (S-IND) oceans.

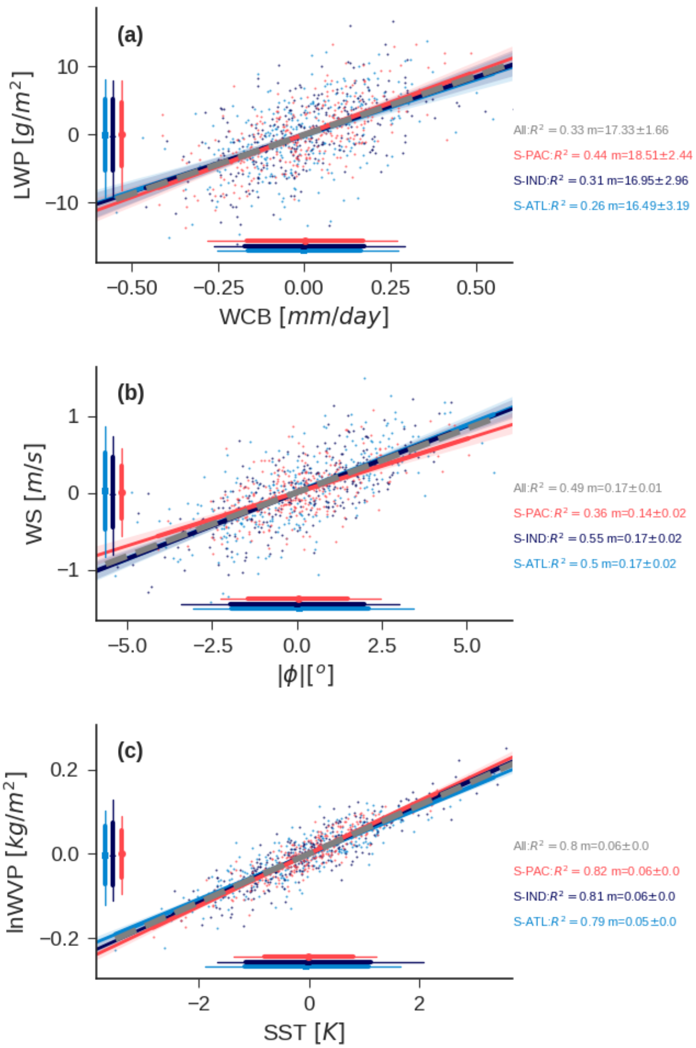


Fig. 2 Observed monthly- and regional-mean anomalies in extratropical cyclone properties in the SH ~~and NH~~ oceans (NH oceans are shown in Fig. S5). (a) Cyclone monthly-mean LWP_{RM} as a function of WCB_{RM}; (b) regional- and monthly-mean wind speed as a function of regional- and monthly-mean cyclone absolute (poleward) latitude; (c) monthly-mean $\ln(WVP)_{RM}$ as a function of SST_{RM}. Each data point in the plot represents the monthly- and regional-mean anomaly in a given variable within extratropical cyclones relative to the monthly-mean climatology. The shaded area corresponds to the 95% confidence interval on the fit. The R^2 and best fit line are listed for each subplot and for each ocean region. The R^2 of all monthly- and regional-mean anomalies is also noted (the variability in regional- and monthly-mean anomalies are weighted equally between regions to calculate the overall R^2). Bars on the sides of the plot show the mean (marker), standard deviation (thick lines) and 90th percentile range (thin lines) of monthly- and regional-mean anomalies for each region.

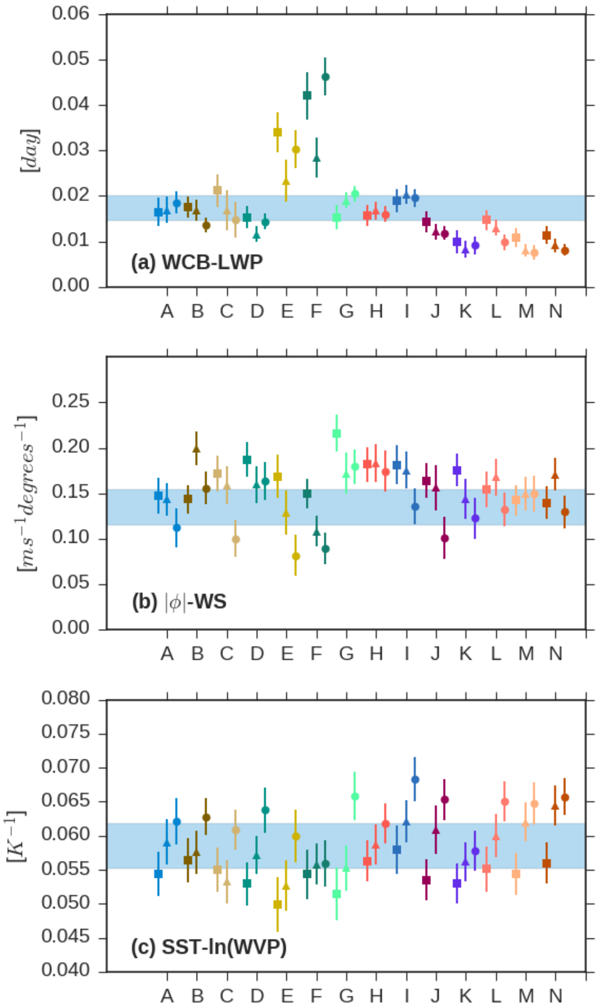


Fig. 3 The slope of the best fit line between monthly- and regional-mean anomalies of different cyclone-mean properties. Symbols denote different SH ocean basins (South Atlantic:squares, South Indian:triangles, and South Pacific:circles). Model colors are as in Fig. 1. Each model is labelled with a letter on the ordinate (~~see Table 1~~see Table 2). The observations are shown as 'A'. The 95% confidence on the slope is noted for each basin. The shaded area shows the 95% confidence on the mean of the observed slope based on the SH ocean basins. (a) shows the slope of the regression of cyclone LWP_{RM} on WCB moisture flux, (b) shows the regression slope of the mean wind speed in cyclones on mean poleward latitude; and (c) shows the regression slope of $\ln(WVP)_{RM}$ on SST_{RM}.

~~Manaster et al. (2017)~~

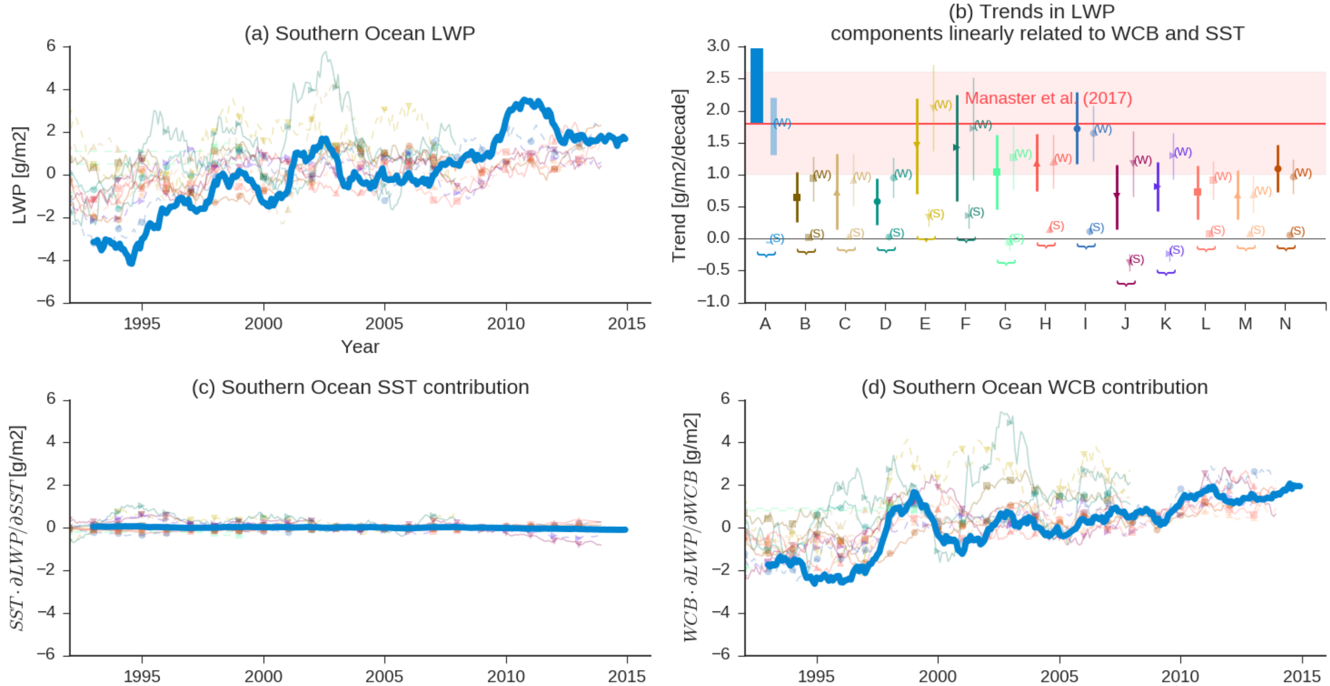


Fig. 4 (a) SH cyclone LWP_{RM} in observations (thick blue line) and models (colors as ~~in~~ in Fig. 1) where cyclones are centered between 44.5°S and 59.5°S. A 2-year running mean has been applied to simplify the plot. (b) The red shaded area shows the zonal-mean Southern Ocean LWP trend calculated in Manaster et al. (2017) (Southern Ocean defined as 44.5°S-59.5°S therein). Trends in cyclone LWP_{RM} from observations and models are shown in dark colors (where LWP_{RM} is calculated using cyclones centered in the same region as Manaster et al. (2017)). Models and observations are labelled by a letter on the ordinate (see Table 2~~Table 2~~). Observations are labelled as 'A'. The 95% confidence in each trend is shown using errorbars. A multiple linear regression of LWP_{CM} on SST_{CM} and WCB moisture flux is used to partition the trend into contributions from WCB and SST changes. The trend in LWP_{RM} predicted by the regression model (Eq. 4) and changes in SST_{RM} is shown in (c), and the trend in LWP_{RM} associated with WCB is shown in (d). The trend from models and observations consistent with their multiple linear regression models and changes in SST_{RM} and WCB is shown in (b) using lighter colors and labelled as (S) for SST, and (W) for WCB.

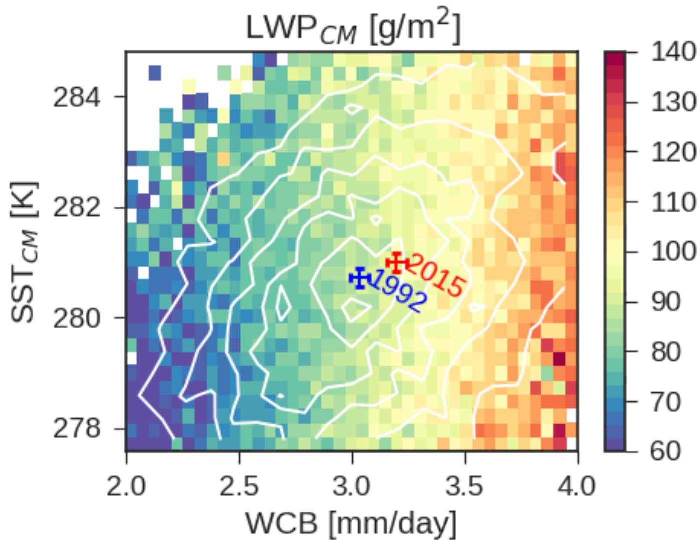


Fig. 5 Average Southern Ocean cyclone LWP_{CM} binned as a function of SST_{CM} and WCB moisture flux for the latitude band 44.5°S to 59.5°S, following Manaster et al. (2017). Contours of cyclone distribution are shown in white. The mean cyclone WCB moisture flux and SST_{CM} for 1992 and 2015 are shown as blue and red points, respectively. Errorbars show the 95% confidence on the mean.

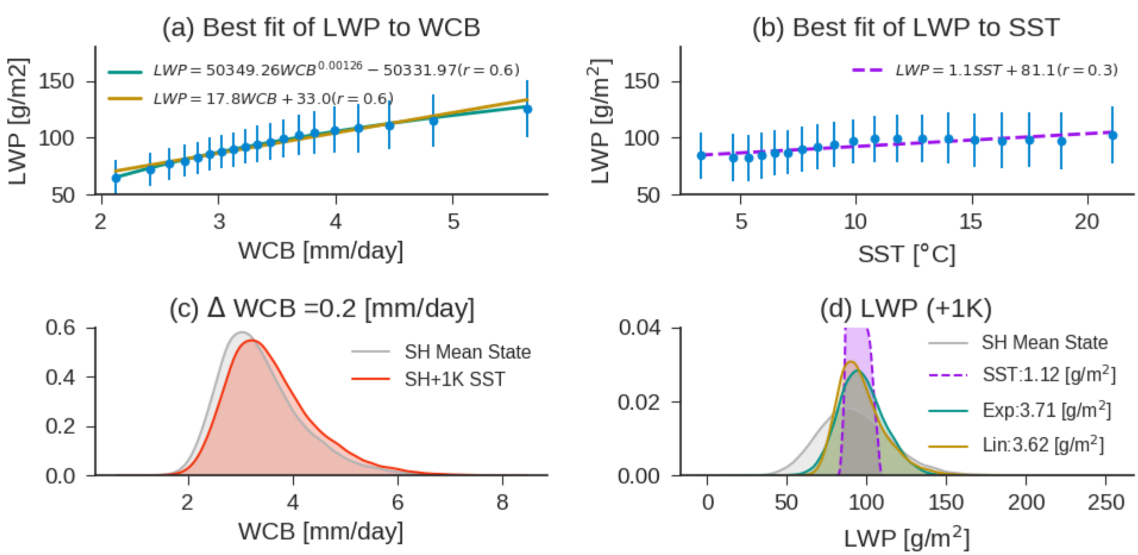


Fig. 6 (a) The LWP_{CM} observed in SH as a function of WCB moisture flux, the best fit line to the observations using the form $LWP_{CM} = a \cdot WCB^b + c$ is shown using a green line. A simple linear fit is shown in yellow. The observations are binned into equal quantiles for visual clarity. Errorbars show a standard deviation within each bin. (b) the fit of cyclone LWP_{CM} to SST_{CM}. (c) The distribution of SH WCB moisture flux in the current climate, and when WVP moisture flux is scaled by 1.06 consistent with a uniform 1K increase in SST. The difference in WCB moisture flux is noted in the title. (c) The distribution of LWP_{CM} in the current

climate and as predicted by the fits shown in (a) and (b). The LWP_{CM} when SST is increased by 1K as predicted by the fits in (a) is based on scaling WVP by 1.06. The $whLWP_{CM}$ predicted by the fit shown in (b) is based on SST increasing uniformly by 1K. The mean difference between LWP_{CM} between the prediction and the climate mean state is noted in the legend.

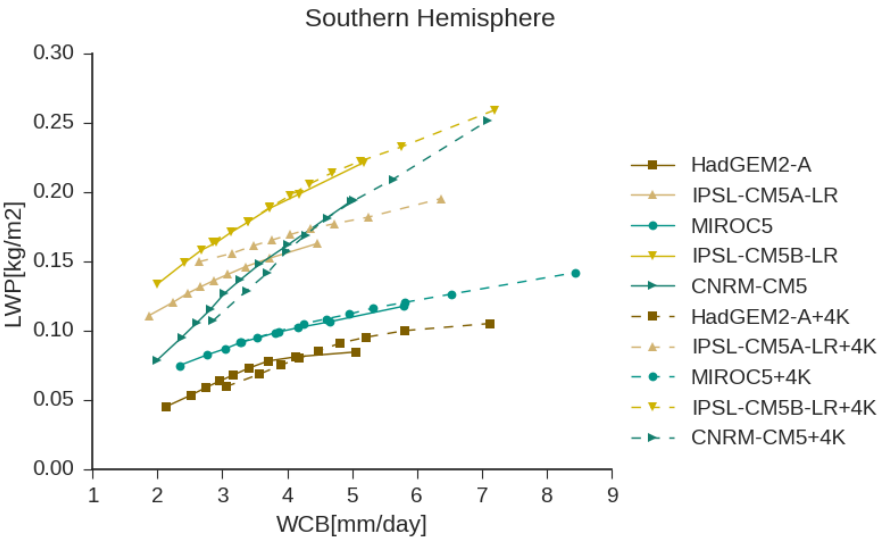


Fig. 7 As in Fig. 1~~Fig. 1~~, but contrasting the AMIP and AMIP+4K simulations in the CFMIP2 simulations.

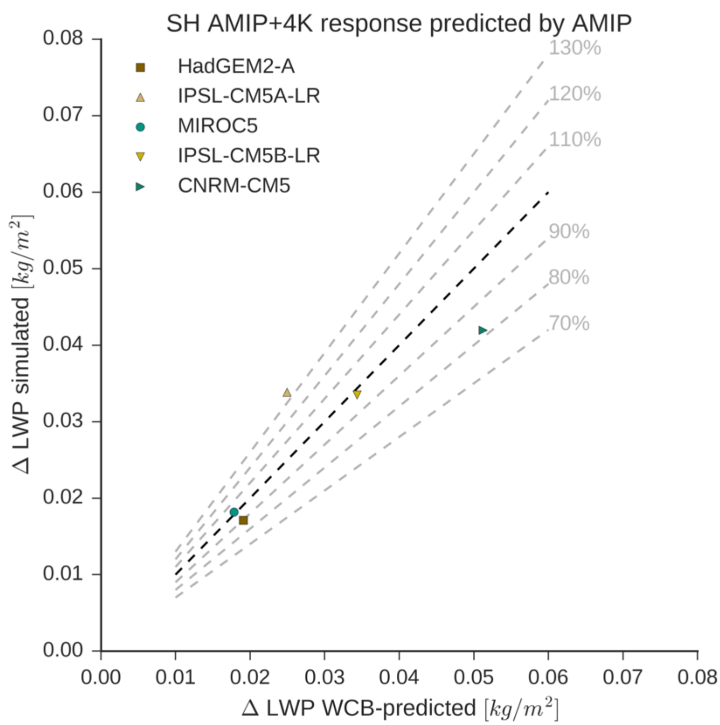


Fig. 8 The difference in cyclone LWP in the SH between AMIP and AMIP+4K simulations versus the difference in SH cyclone LWP inferred from changes in WCB moisture flux and the relationship between WCB moisture flux and LWP_{CM} in the current climate. The one to one line is shown as a dark dashed line.

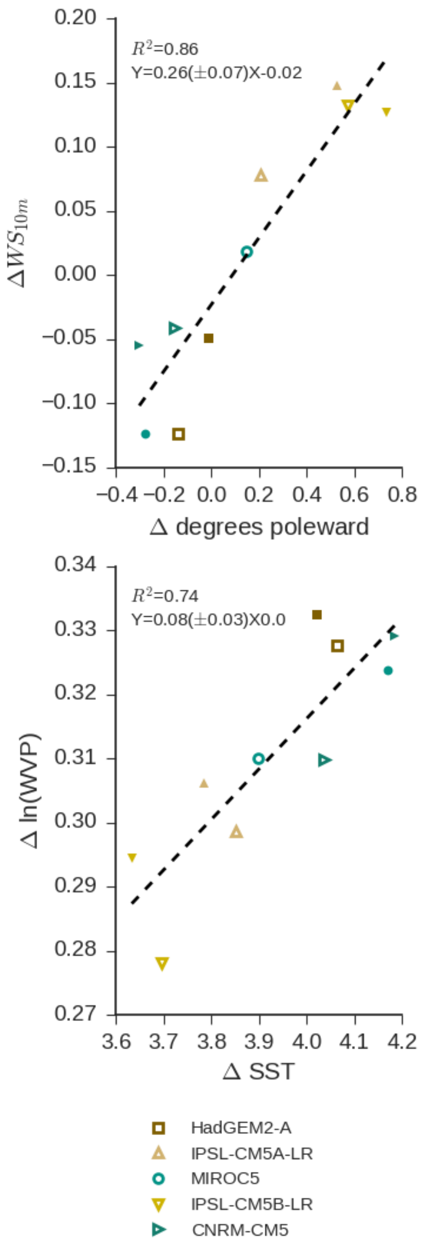
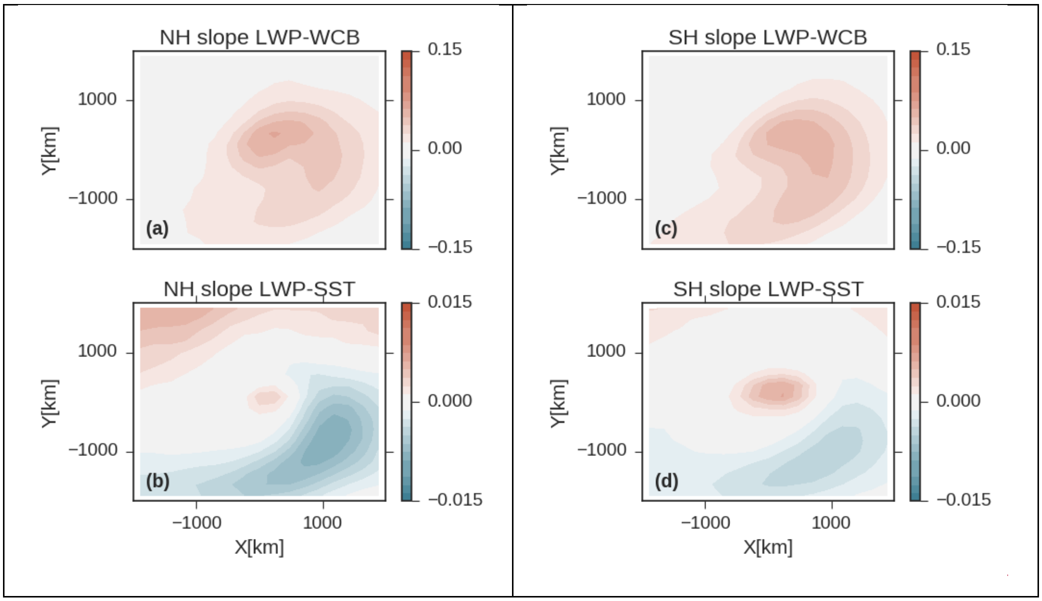


Fig. 9 Changes in cyclone-mean wind speed at 10m (WS_{10m}) and the natural log of WVP between AMIP and AMIP+4K simulations plotted against changes in mean poleward cyclone latitude and SST, respectively. Open symbols show the change over the NH and closed symbols show the change over the SH. The best fit line to NH and SH is noted in each plot along with 95% confidence in the slope.



~~Fig. 9 The multiple linear regression coefficients (Eq. 6) relating observations of LWP_{ij} to SST_{ij} and WCB moisture flux in the NH (a and b) and SH (c and d). Multiple linear regression is used to partition LWP_{ij} into contributions from SST_{ij} and WCB moisture flux. (a) and (c) show the slope of the linear regression between the WCB moisture flux into the cyclone and LWP_{ij} within the composite (units are kg mm day^{-1}m^{-2}). (b) and (d) show the regression coefficient relating SST_{ij} and LWP_{ij} (kg m^{-2}K^{-1}). Note that SH cyclones have been flipped vertically so that the top of the plot is to the pole to facilitate comparison to NH cyclones.~~

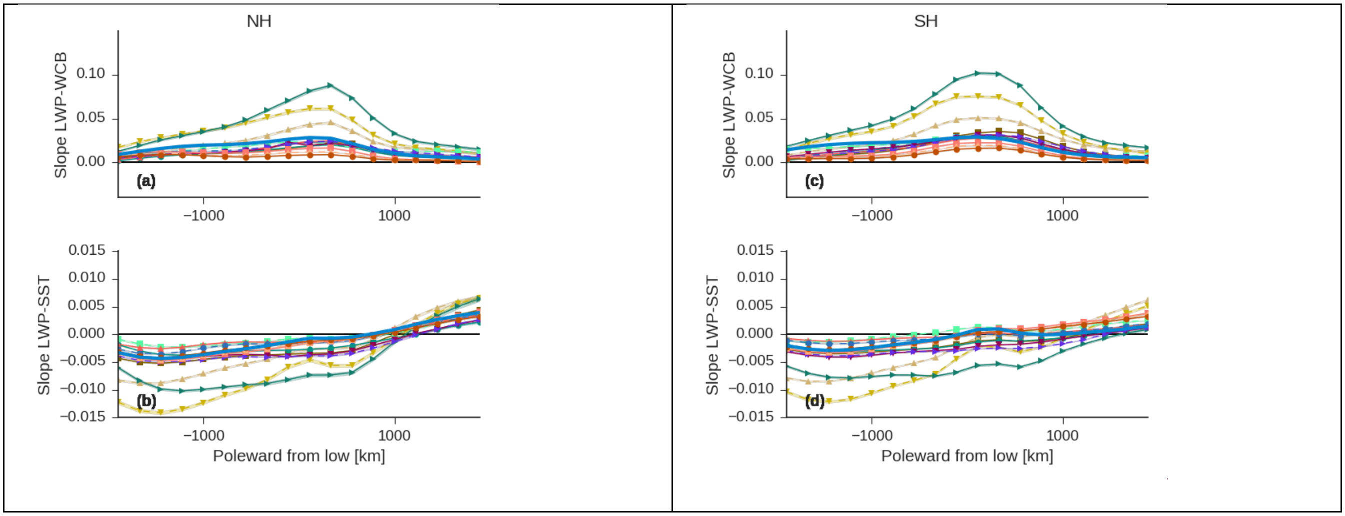
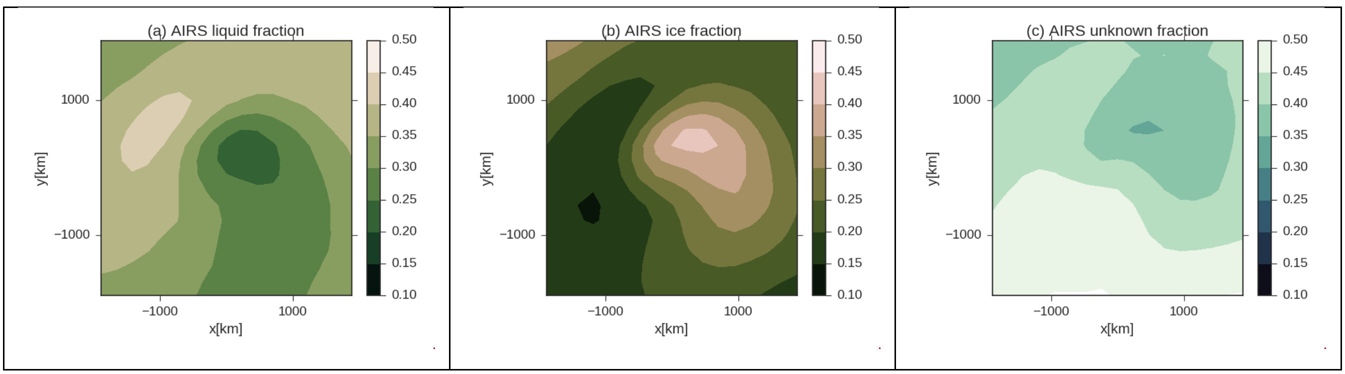


Fig. 9 As in , but showing the multiple linear regression slopes averaged zonally (Eq. 6) across the composite. The x-axis shows distance from the low pressure center oriented toward the pole. Regression slopes from the NH are shown in (a-b) and SH slopes are shown in (c-d). (a) and (c) show the slope relating the WCB moisture flux into the cyclone and LWP_{ij} (units are kg mm day^{-1}m^{-2}). (b) and (d) show the slope of the regression relating SST_{ij} and LWP_{ij} (kg m^{-2}K^{-1}). The 95% confidence intervals in the zonal-mean regression slope are shown as shading.



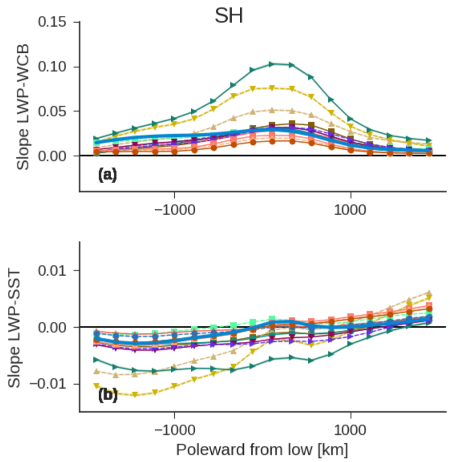


Fig. 10 The multiple linear regression slopes from Eq. 6 averaged zonally across the composite. The x-axis shows distance from the low pressure center oriented toward the pole. Regression slopes from the NH are shown in (Fig. S13). (a) shows the slope relating the WCB moisture flux into the cyclone and LWP_{ij} (units are kg mm $day^{-1}m^{-2}$). (b) shows the slope of the regression relating SST_{ij} and LWP_{ij} (kg $m^{-2}K^{-1}$). The 95% confidence intervals in the zonal-mean regression slope are shown as shading.

Fig. 11 Fraction of liquid (a), ice (b), and unknown (c) cloud top phase from AIRS. Fractions are averages over the period 2003-2015 and are for both hemispheres.

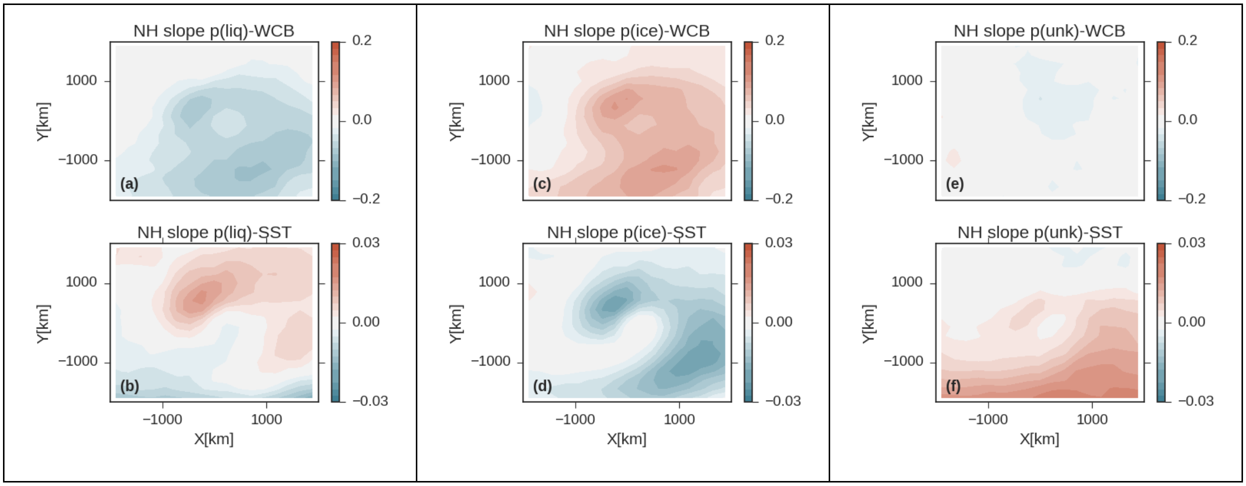


Fig. 11 as in , but showing the coefficients in the multiple linear regression relating the probability of liquid, ice, and unknown cloud top phase to WCB moisture flux (units are day mm^{-1}) into the cyclone and SST_{ij} within the cyclone (units are K^{-1}, Eq. 6). All data is from the NH. (a and b) relate to the probability of liquid topped clouds, (c and d) relate to ice-topped clouds, and (e and f) to unknown phase. Note that all probabilities are the probability of detecting a specific phase, given that a phase detection has been made. The first row shows the coefficient relating WCB moisture flux into the cyclone to cloud top phase probability. The second row shows the coefficient between SST_{ij} and cloud top phase.

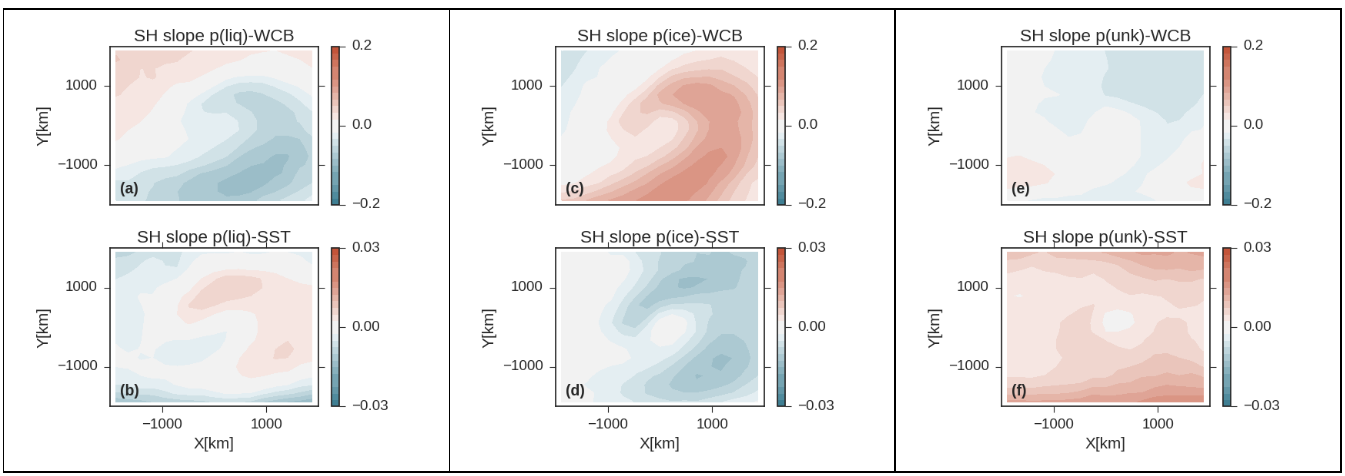


Fig. 12 as in Fig. 11~~Fig. 11~~, but for the SH.