

Dear Dr. William Roberts,

We would like to express our gratitude to the editor and reviewers for their time and work in evaluating our paper. The ideas aided in further improving the research. Additionally, we identify the significant modifications we made to the paper throughout the editing process. We have addressed the following points in particular:

- The introduction was reduced and made more succinct
- Our methods now include the Fisher z-transformation, improving the statistical robustness of our results
- We further expanded on the caveats of using a 4x forcing in our models
- Sections 3.1 and 3.2 were made more succinct and refined with further explanations for why the reader should care
- Sections 3.3 and 3.4 were improved by changing the significance test in subfigure (f) to be (1) more consistent with the all subfigures, and to (2) outline the significant differences better between P and AP experiments
- Section 3.4 was improved and edited to include the Fisher z-transformation confidence intervals and to indicate where the Atlantic SSTAs both significantly and insignificantly modulate ENSO's connection to the NAE region

Please find the detailed responses to the reviewer's comments and suggestions below.

Jake Casselman, on behalf of all authors

REVIEWER COMMENTS:

All changes in the text have been **boldened**, and explanations for each comment are stated below the comment in **blue** writing.

Reviewer #1:

SUMMARY:

The study is about inter-basin interaction of the Walker Cells and Gill responses forced by ENSO-related SST in the Pacific and Tropical North Atlantic during boreal spring and summer, as well as their teleconnection to the North Atlantic. Analyses from reanalyses and atmospheric model experiments are performed.

I think this is an interesting and important topic. However, currently, I find that the main problem is the presentation/writing lacks connections among the every smaller piece of results described. This is perhaps due to the reason that there is a lack of explanations on how the different pieces fit together. The paper in some parts reads like a mere listing of many features found, and it is easy to become lost for the readers. I describe this issue in a number of specific subsections below.

I also have some questions about clarifying what relationships are being modulated and what are the modulators.

MAJOR COMMENTS:

Sects. 3.1, 3.2: There are various features and properties identified and described. I find it somewhat difficult to digest because I am not quite clear about what are the reasons for highlighting those specific features. I suggest to consider the main aims of the study when selecting features that are essential to focus on, and tell us also exactly why we should look at them in relations to the central questions of the study and how they link to the next subsections.

Section 3.1 begins by answering the first part of our goals, namely the tropical interactions, by considering how the TNA and ENSO interact in reanalysis. We state this aim: “identify the respective influences each equatorial region may have on the Walker circulation” (line 178). These results from reanalysis later serve as a comparison when using our model in order to understand how the basin interactions are represented in the model. To improve section 3.1, we have removed the sentences between lines 190-192 as they do not directly address this goal, allowing us to combine paragraphs 2-3, making section 3.1 a succinct 3 paragraph description of reanalysis.

Subsection 3.2 aims to address the differences in timing between the influences of each tropical basin on the tropical circulation and to introduce and justify the Walker cell index and Caribbean RWS index by showing that there is a significant connection between both indices. To make the subsection clearer we have done several adjustments:

- We have moved “**As we are interested in the respective influences from each equatorial basin onto the Walker cell, and the resulting upper level RWS over the Caribbean, we create a large-scale streamfunction gradient index between the Pacific and Atlantic, centered over the Caribbean. We complement this index with a more localized RWS index over the Caribbean.**” into first paragraph to help move the justification closer to the beginning.
- We rearrange the justification sentence from “By using a lead-lag analysis, we further determine the dominant seasons for relating each indicate to the tropical basins.” towards: “**We use a 24-month lead/lag correlation analysis to analyze the Walker cell relationships, and to further understand how connections with ENSO and the TNA change between MAM and JJA.**”

Sect. 3.3: This is again a rather long catalogue of different combinations, comparisons and observations of the model results. It is not described clearly why all the different results should be of interest in connection with the central themes. Yes, ok, there is a linear constructive/destructive effect, there is also some nonlinear effect in certain features, and there are some agreements and disagreements with the reanalysis data. But try to tell us why they are important in their own right and/or for the central themes.

Thank you for your feedback on this subsection.

Subsection 3.3 pertains to tropical inter-basin interactions, and follows the goal stated at the end of the introduction (First, to analyze the tropical modulation of the TNA on the ENSO teleconnections, then how this modulation influences the extratropical connection of ENSO onto the North Atlantic. We further place key attention on the linearity, and the timing, as well as contrasting reanalysis and our sensitivity model runs (outlined on lines 89 to 92)):

We describe the main rationale behind considering the results in the following:

- Why should we look at model data and not reanalysis (lines 238-245)
- Why we should consider A, P, AP, A+P, AP-(A+P), and AP-P (lines 246-253)
- Why we look at the Walker cell (lines 254-255)
- Why we also use the streamfunction (lines 300-301)

To make the subsection feel less “catalogue”-like, we improve the manuscript by including the following:

- Improving explanation for moving from an MLR to a model by changing **“However, this method can be misleading and limits our ability to explain nonlinear relationships as it assumes that the effects from each basin onto the Walker cell are additive...”** To: **“However, this method cannot fully capture the nonlinear contribution, as it assumes that the effects from each basin onto the Walker cell are additive...”**
- In order to further state the reasons for looking at A, P, AP, A+P, AP-(A+P), and AP-P, we edit the section to now read: **“In order to address the sensitivity of ENSO to the TNA SSTAs, we determine the separate and combined influence of both basins using separate forcings for the Atlantic (A), Pacific (P), as well as both basins forced simultaneously, i.e., Atlantic+Pacific (AP). To determine the linearity of ENSO’s response to the addition of the Atlantic SSTAs, we also look at the linear addition (A+P) of the responses from each basin in comparison to the simultaneous forcing (AP), and calculate the difference between forcing each region...”**
- To further justify the streamfunction composites, we add the explanation that **“As the Secondary Gill and asymmetric Gill type responses have distinct**

spatial patterns in streamfunction, composites analysis shows the inter-basin interaction from a different perspective than the Walker cells” near in line 301 of the original manuscript.

- We increase the focus on AP-P (i.e., the influence from the Atlantic forcing on modulating the Pacific ENSO atmospheric teleconnection) and away from the linearity by changing the significance test for figure 4f and 5f from the difference between (AP-P) vs A and towards simply (AP) vs (P) and put all (AP-P) vs A figures in the supplementary section. This also further increases our statistical significance and makes the subfigures more consistent. We also made this change for figures 6, 7, 9, 10 to be consistent.

Fig. 8: You are making comparisons between the correlation coefficients r . I have doubt that some of the differences you describe are statistically significant. I think you should at least check with Fisher z-transformation, find the confidence interval, then transform it back to r . Then you can present each correlation coefficient in a range, based on the significance level you decide. If the uncertainty range overlap between two experiments then the difference is not statistically significant. Here is an example that presents such information in their results:

Revisiting the relationship between jet position, forced response, and annular mode variability in the southern midlatitudes

<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2016GL067989>

(see their Figure 2).

Thank you for the great suggestion. We indeed did not compare the significant difference between R values, only the significance of the R independently. We have implemented the analysis and results show that the uncertainty ranges are very large, and the intervals overlap between the different correlation values. However, this outcome improves the consistency between our analysis that used changes in R to determine sensitivity and the analysis that uses composite analysis. Therefore, the overall conclusions are not changed in a significant way. To incorporate this new finding into the manuscript by including the following:

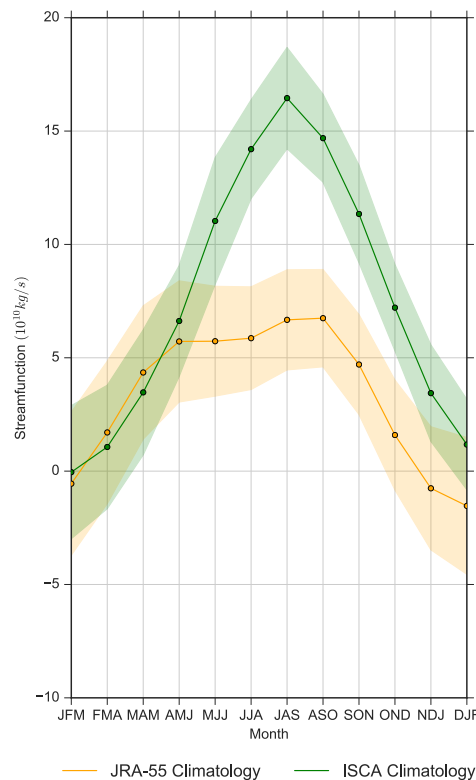
- Slight modifications throughout for better reading (see bolding)

- Inclusion of method in the methodology, including: **“We also use correlation (R) throughout, and derive significance by using a confidence interval created by using a Fisher transform (Devore, 1991; Simpson and Polvani, 2016).”**
- Changing the phrase (around line 336 in original manuscript) “When forcing both basins together (AP), the correlation increases by 57% to -0.44 as compared to only forcing the Pacific basin (P)” to now read as: “When forcing both basins together (AP), the correlation increases by 57% to -0.44 as compared to only forcing the Pacific basin (P), **but we find that the difference is not statistically significant (see confidence intervals in Figure 8a).**”
- We compared the insignificance between the change in the Walker index-RWS with the significant change in RWS anomaly to help further emphasize that the Walker cell may not be the only aspect influencing the relationships
- Point out the insignificance for the Walker-EA relationship, which corresponds well with the proceeding observation that the EA anomaly changes little (lines 356 in original manuscript, 363 in new manuscript)
- The insignificant correlation change also helps make the scatter plots more consistent with the composite analysis, and where possible the writing was updated to reflect this improved consistency.
- In the conclusion we also include: **“Thus, when examining the effectiveness for Atlantic SSTAs to modulate of the extratropical response through using correlation shifts, we do not see a significant strengthening of the link between the Walker cell gradient and either EA or NAO in both boreal spring and summer.”**

Fig. 8: Are the scatters (dots) in each experiment due to internal variability in the same experiment? Or each dot represents one experiment? The SST forcing is the same for a same season year by year, right? I am a little surprised by the 'large' variability of the Walker Index. I thought tropical circulations are much less 'noisy' under the same SST forcing. Would it be useful to add the reanalysis data (under El Nino condition if you like) in these plots for comparison? I understand they won't be then comparing the same things, but it could give us an idea both on what the variability and the relationships between these indices are like in the reanalysis data.

Thank you for sharing this point of concern. Each color represents one experiment type (i.e., A, P, AP). As we previously ran analysis on the basic state, including the seasonal evolution for both JRA-55 and ISCA's climatological experiment, we

believe that the large variability is reasonable and within the bounds of observed internal variability. To help further show this, we included the seasonal evolution of the Walker cell below. As seen in MAM and JJA, ± 1 stddev has a spread of approximately 5×10^{10} kg/s for both JRA-55 and ISCA, which is approximately the same as the crosses in figure 8 (horizontal width also represents ± 1 stddev). Indeed, some parts of the seasonal evolution show that ISCA has a smaller spread ('less noisy'), but this is likely due to the lack of interannual variability.



Lines 440-448: I am not sure this argument works nicely. You are using the observation that there is near-zero RWS from non-zero Walker Index anomaly for P (from Fig. 8a?) and that RWS is related to the Walker Index, to argue that the modulation from the tropical Atlantic in the AP is important to improve relationship of RWS and the Walker Index. But the AP experiment also has a problem of having average near-zero Walker Index anomaly, so how does that result in a non-zero RWS anomaly that is obtained? Maybe there is another factor not considered here and the Walker cell is not suitable factor. Also, you might have mixed up two things

in your descriptions here: the average response of the experiments (compared to Control experiment) and the modulations by the SST forcings on the internally-generated RWS and Walker Index relationships. Or it's possible I have misunderstood Fig. 8, see my question about Fig. 8 above. In any case, I think further improvement in the descriptions and making the arguments is required.

Leading up to line 440, between lines 438 and 440, we explain that we are looking at the correlation, and that there is nearly a doubling of R between P and AP (for the Walker vs. RWS indices). Between lines 440 and 442 explicitly point out that this strong correlation difference is incongruent with the observation that P has little RWS but a negative Walker cell gradient (line 440, "It is notable that although the Walker index and RWS have a strong relationship, the linear fit does not pass through the origin, whereby the P has a strongly negative Walker index but lacks an anomalous RWS"). This incongruity was also explicitly pointed out the similar issue in the Results section, on lines 346-348 ("Since the mean RWS for P is neutral even with a strongly negative Walker gradient, this indicates that the Walker gradient is not the sole influence on the Caribbean RWS.").

To further improve the description, and to help our argument, we further state that:

"Finally, to further understand the neutral mean response for P , Supplementary Figure S5 shows the RWS field. We find that only the sensitivity experiments that force the Pacific (P and AP) have a strong negative RWS over the Gulf of Mexico and that this RWS response dominates over the negative RWS over the Caribbean. This RWS may be related to the most southeastern lobe of the PNA pattern, as it strongly overlaps with the Southeastern low presented by Casselman2021 et al., (2021). As a result, even as the Walker cell index may tend towards inducing a positive RWS when forcing the Pacific only, the influence from the Southeastern low may dominate over the influence from the Walker gradient, potentially explaining why the RWS is neutral for P , as opposed to positive." (around line 350 in the updated manuscript)

Paragraph in Line 464, Fig. 8b, c, and the title of the paper: If I have understood Fig. 8 correctly, I think Fig. 8 is mostly presenting something fundamentally different from Figs. 6, 7 (and 9, 10). For eg, Fig. 8b, c is about how both ENSO and the related tropical North Atlantic SST modulate the relationships between the Walker Index and EA (and also NAO), whereas Figs. 6, 7 instead are mainly about the point of how

ENSO teleconnection is modulated by the tropical North Atlantic (like the paper title). In the former, ENSO is one of the modulators; in the latter, ENSO teleconnection is being modulated. Therefore, Fig. 8 is also not directly related to the title of the paper. (See also the previous comment).

Thank you for your comment. Figures 8b-c are about of the tropical connection to the extratropics following an ENSO event and how it is modulated (moving from the red to the yellow cross) by the presence of the Atlantic SSTAs. To the extent that we look at how the Atlantic SSTAs (independent of Pacific SSTAs) are related to this connection, we primarily use this to help explain why we see the shift from red to yellow.

In this figure, we analyze the changes in the correlation between EA/NAO and the Walker cell with respect to the different SST forcings, showing the modulating role of to the Atlantic SSTAs on the ENSO extratropical connection. Figures 6,7,9,10 use shifts in composite anomalies to show how sensitive the ENSO influence on the extratropical (and tropical for 6,7) is to the Atlantic SSTAs, and to the extent that we look at how the Atlantic SSTAs (independent of Pacific SSTAs) are related to the extratropics, it is to simply help explain why we see the shifts between P and AP. In 6,7 we are actually framing our analysis more towards ENSO perturbing the Walker circulation (including downstream towards the Atlantic) as a teleconnection, from which the Atlantic SSTAs modulate. In Figures 9 and 10 we are also framing our analysis more towards ENSO extratropical teleconnection, from which the Atlantic SSTAs modulate. Therefore, we believe that figures 6-10 show and quantify different aspects of the TNA modulation of ENSO teleconnections.

To incorporate your feedback, we have modified the title (which can be found in the minor comments section), and also further justified our use of correlation at the beginning of subsection 3.4, stating: **"We use changes in both the correlation and mean anomaly between *P* and *AP* to quantify how sensitive ENSO's teleconnections are to Atlantic SSTAs."**

MINOR COMMENTS:

Title of paper: Most papers on similar subject would be on the cold seasons, if this is about boreal spring and summer, I think it should be reflected in the title.

Thank you for the suggestion, and we agree with the point made. We have changed the title from:

“Modulation of the ENSO teleconnection to the North Atlantic by the tropical North Atlantic and Caribbean”

to:

“Modulation of the El Niño Teleconnection to the North Atlantic by the Tropical North Atlantic during Boreal Spring and Summer”

Paragraphs in Lines 67-82: Shorten these substantially. They read like an information dump and are not easy to follow. They also appear to disconnect the subsequent and preceding paragraphs, where you are already building up to the aims of the study. So, they might be relocated to an earlier part of Intro.

Thank you for your suggestion. We reduced some of the wording, removed the warm pool section and moved the references to the first paragraph of the results for justifying the JJA season selection. Overall, we were able to shorten it substantially and combine the two paragraphs into one.

Sentences in Lines 88-92: Which seasons/months do you focus on?

Thank you for pointing this out. We have added further information on lines 90 and 91 including: “We consider the inter-actions between the tropical basins, as well as interactions between the tropics and North Atlantic **during boreal spring and summer.**”

Sect 2.2 heading: Change to "Model description and experiments".

Thank you for your suggestion, we have changed the title from “Model description” to “Model description and experiments”

Line 122 "We chose to multiply the forcing by 4": Is this a realistic forcing? Would this be an obstacle for using the model results to interpret observed relationships or to understand the real world, considering also there might be the potential issue of nonlinear teleconnections due to forcing amplitudes?

Thanks for your feedback. We are aware of the potential for the nonlinearities, and originally informed the reader on line 122-123 that this forcing was stronger than observations. The rationale for using 4 was to ensure a strong response, but with a clear limitation being that it is more difficult to compare to the real world.

In order to reiterate this, we have added further explanation including: **"Furthermore, the atmospheric response to the SSTA forcing may experience nonlinearities (i.e., upper-level divergence responds nonlinearly to a linear change in the magnitude of Pacific SSTAs), but given our analysis is during boreal spring and summer when Pacific SSTAs are weaker than boreal winter, any nonlinearities may also be weaker than those during boreal winter (Graham and Barnett, 1987; Sabin et al., 2013) "**.

Paragraph in Line 126 and last ever: WHY do you want to "remove the indirect influence from stratospheric variability"? Again, what does this mean in the limitations of using the models results to understand the real world? Isn't it easier to not apply the relaxation in the first place? Perhaps you should also perform experiments without the relaxation now? Why wait for another future study? Are the experiments very expensive to run?

We thank you for your comment and can understand this point of view as it was a major point of discussion on how to format the study. In the end we are aiming for a paper that explicitly focuses on the interactions within the troposphere to better understand the relationship. This choice eliminates the ENSO pathway through the arctic (i.e., the stratospheric pathway), and highlights the pathway through the troposphere, which can occur through the Caribbean. To help emphasize this, we have added:

"While ENSO teleconnections towards the North Atlantic can travel through either the stratosphere or troposphere (Jiménez-Esteve and Domeisen, 2018), teleconnections that travel through the Caribbean are tropospheric (Hardiman et al., 2019), and hence our study focuses on the tropospheric pathway only."

The implications of this choice have already been outlined in the final paragraph of the conclusion (492-498), including how this choice may influence the variability in the North Atlantic, but to a lesser extent as the stratosphere is less active in boreal summer. Furthermore, due to the length of paper that doing both types of studies within the same paper, we have focused on one aspect only.

Line 123 "we aim to determine the importance of the TNA following an El Nino only": Is there a reason choosing to only look at El Nino?

We focus specifically on El Niño to keep the paper within a reasonable length. A complementary study on the interactions during La Niña would also be beneficial and a potential next step beyond this paper.

Line 261 and other places: "Sensitivity experiments": In my view, these are not sensitivity experiments because we don't get a sense of how sensitive the model response is to the change of an input strength.

Thank you for your suggestion. We have replaced the wording "sensitivity experiments" throughout the manuscript following your comment.

Line 334 and other places, "sensitivity runs": Same as above, I would not call these sensitivity runs.

Same reason as stated in the minor comment above.

Figs. 6, 7 and Figs. 9, 10: Is it really essential show both pairs of figures (psi and Z200)? Maybe it's enough to only show results in psi, and reuse the same figures in the description in Sect. 3.4. Extratropical (for a geostrophic argument) geopotential height and psi at 200hPa are related with a factor of the Coriolis parameter.

Thank you for the suggestion, and we have also deliberated over this in the past, as there are indeed many aspects that overlap. However, we feel that although the fields are highly related, the benefit of including both (such as the differences in boreal summer in the NAE region, fig. 7a-b vs. fig. 9a-b) outweighs the drawback of not.

Fig. 8: Have you specifically refer to or describe the dark straight line and the legend for R written in black?

Thank you for pointing this out. This black line was originally the correlation across all simulations, but we have removed the dark line as well as the R written in black as we no longer refer to this in the manuscript.

Fig. 8: Sorry to be pedantic. The correct way to describe these plots is "Y vs. X", not "X vs. Y" as you write.

Thank you for pointing this out, we have changed the subfigures titles in figure 8 to the correct order of "Y vs. X".

Line 382: This description is not precise or not correct. Fig. 9e obviously shows an EA pattern, yet you say it is "less present". Perhaps what you try to say is simply the negative EA pattern in AP is not as strong as the negative EA pattern from A+P (?).

Thank you for pointing out this error, you are indeed correct with your assumption for the meaning, so we have changed the sentence to read as: "The EA pattern in figure 9e indicates that when forcing the two basins simultaneously, the **negative** EA pattern is **weaker** during AP than when linearly adding the two basin forcings (A+P)."

Reviewer #2:

The authors use observational analysis and model experiments to investigate the role of tropical North Atlantic (TNA) in modulating the ENSO teleconnection during boreal spring and summer. The inter-basin relationship between the equatorial Pacific and Atlantic is also examined in this study. This is a potentially constructive contribution to our understanding of how TNA modulates the influence of ENSO on the North Atlantic European region. However, this paper is a little difficult for the reader to follow. There are too many different analyses and indices, but an explanation that ties everything together as a whole story is lacking. I discuss these issues in detail below.

Shorten the introduction. There is too much information and each paragraph is disconnected.

Thank you for the suggestion. We have removed items that we felt were unnecessary, Including:

- Reduced the areas between lines 67-82 and removed warm pool items, and combine two paragraphs in this part of the manuscript
- Around line 26 we also reduced the number of examples for how teleconnections are sensitive as this added
- Lines 46-49 were unnecessary and removed, while the paragraphs surrounding these lines were combined

Line 120 "...regression values are multiplied by 4...": The maximum of the SSTA in the Pacific looks too strong ($\sim 4^{\circ}\text{C}$) and may not appear in the observations. Since you consider the non-linear process of the ENSO influence, too strong ENSO amplitude can lead to an unrealistic ENSO response. The caveats of this approach should be discussed.

Thanks for your feedback. We are aware of the potential for the nonlinearities, and originally informed the reader on line 122-123 that this forcing was stronger than observations. In order to help explain the caveats, we have added further explanation around line 120 including: **"Furthermore, the atmospheric response to the SSTA forcing may experience nonlinearities (i.e., upper-level divergence responds nonlinearly to a linear change in the magnitude of Pacific SSTAs), but given our analysis is during boreal spring and summer when Pacific SSTAs are weaker than boreal winter, any nonlinearities may also be weaker**

than those during boreal winter (Graham and Barnett, 1987; Sabin et al., 2013)
“.

Section 3.1 and 3.2: I understand that the authors wanted to focus first on the tropical interactions. However, too many features are pointed out here (Walker index, RWS, PCD...). This makes it difficult for the reader to understand and to know how these features are related to your main question. I suggest reorganizing these two sections and relating these characteristics to your main question before and after the analysis. Why are we discussing the walker index, RWS, PCD..., and what we know from these features?

Thank you for the suggestions. We have made the following changes:

- In section 3.1's final paragraph we further elude towards the PCD and Walker index connection to further explain the connectedness
- In the beginning of 3.2 we further explain why we need to do a correlation, as well as why we look at the PCD, including: **“We compare the PCD to the Walker cell gradient, as it is hypothesized that both mechanisms are highly related.”**
- At the end of subsection 3.2 we also explain: **“Furthermore, as the Walker gradient and PCD are highly coupled, for the remainder of this paper, we use only the Walker cell gradient.”** Here we are able to reduce the scope and focus on two main tropical interactions—a large scale (Walker gradient) and a local scale (Caribbean RWS).
- The rationale for using the PCD for the first section is to relate to past studies and to validate the hypothesis that the PCD is likely related to the Walker cell gradient.

Lines 208-213: Here is a summary of the previous section. It is better to move this part to the end of the previous section.

Thank you for the great suggestion, we have moved the paragraph to the previous subsection.

Line 216: Although the authors have defined the indices in the Methods, I suggest simply re-stating them in the text when they first appear.

Thank you for your suggestion. For the less common indices (so excluding Nino3.4 and TNA) we included a reminder in brackets for the reader.

Figure 3: Only the upper part of the panel is discussed (TNA, ENSO, PCD lead Walker index). It is unnecessary to show the bottom part of the panel [Walker Index JFM(0)-DJF(0)].

Thank you for pointing this out. We originally discussed the RWS-Walker correlation on lines 234-236, but mistakenly left out the reference to the figure, which we now include.

Lines 238-240: Here is a summary of the previous section. It is better to move this part to the end of the previous section.

Thank you for the feedback. Lines 238-240 relate more towards subsection 3.1 (MLR and Walker cell), so moving it wouldn't be appropriate for the previous subsection (correlation analysis). Therefore, we believe it is best to keep the 2 lines in this area.

Figure 4: Delete the “200 hPa” from the title.

Thank you for pointing this out, we have also removed the 200 hPa from figure 5 for the same error is present.

Line 340 “the Walker response to AP forcing is approximately 0 for both season”: This is not correct. It should be “varies around 0”.

Thank you for the suggestion, we have now changed the manuscript to use “varies around 0”.

Figure 9 & 10: The information in these two figures is almost the same as in Figure 6 & 7. The authors can just use Figure 6 & 7 directly to discuss the ENSO teleconnections.

Thank you for the suggestion, and we have also deliberated over this in the past, as there are indeed many aspects that overlap. However, we feel that although the fields are highly related, the benefit of including both (such as the differences in boreal summer in the NAE region, fig. 7a-b vs. fig. 9a-b) outweighs the drawback of not. For example, streamfunction is much better at showing Matsuno Gill type responses, while struggles to show anomalies over Europe.

Figure 6 & 7: The authors can mark the EA and NAE regions in these figures. This makes it easier for the reader to understand.

Thank you for the suggestion. We have added the EA box in the North Atlantic, but we do not define the NAE region in the paper and therefore also do not put box.

Modulation of the El Niño Teleconnection to the North Atlantic by the Tropical North Atlantic during Boreal Spring and Summer

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Abstract. El Niño Southern Oscillation (ENSO) can bring about inter-basin interactions, whereby Pacific sea surface temperature anomalies (SSTAs) may influence the North Atlantic European (NAE) region. However, ENSO’s overall influence on the NAE remains unclear. One potential reason for this uncertainty may arise due to the region being dominated by several different mechanisms. Here we focus on one potential region, namely the Tropical North Atlantic (TNA), and determine how the SSTAs modulate the ENSO teleconnection towards the NAE region. As numerous pathways from the TNA may exist for this modulation, we further center our analysis onto the Caribbean region and Walker cells. We force an idealized atmospheric circulation model with three different seasonally varying sea surface temperature patterns that represent an ENSO event with or without the influence of the Atlantic. Our results demonstrate that modulation of the NAE region by the TNA SSTA and Caribbean region occurs in the boreal spring and summer following an ENSO event. In boreal spring, this modulation is primarily through a propagating Rossby wave train, while in the summer, the TNA’s influence is nonlinear and tends to strengthen the ENSO influence over the NAE sector. Overall, this study offers a deeper understanding of the inter-basin interactions of the Walker cell following an ENSO event and the central role of tropical Atlantic SSTAs in modulating the teleconnection to the NAE region.

1 Introduction

El Niño-Southern Oscillation (ENSO) dominates interannual variability within the tropics and has global impacts through teleconnections. In addition to impacting the tropics, teleconnections can also influence extratropical regions, such as the North Atlantic European (NAE) region (Fraedrich and Müller, 1992; Fraedrich, 1994; Brönnimann, 2007). While it is not yet fully understood how ENSO impacts the NAE region, there is great potential for ENSO to create a relevant impact, which in turn may benefit long-range predictability over Europe (Domeisen et al., 2015). The complexity present in the ENSO-NAE teleconnection results in part from several ENSO teleconnections influencing the region simultaneously. These pathways can be separated into several different parts, including signals through different geographical regions as well as different atmospheric levels (Rodríguez-Fonseca et al., 2016). For example, teleconnections can propagate through the extratropical troposphere (Bulić and Kucharski, 2012; Jiménez-Esteve and Domeisen, 2018; Mezzina et al., 2020), the extratropical stratosphere (Butler et al., 2014; Ayarzagüena et al., 2018; Domeisen et al., 2019), or the Caribbean region (Wulff et al., 2017; Hardiman et al.,

25 2019; Rieke et al., 2021). Furthermore, different regions modulate the regional response to ENSO teleconnections, such as the tropical North Atlantic (Sung et al., 2013; Casselman et al., 2021), and the Indian Ocean (Zhong et al., 2005; Fletcher and Cassou, 2015; Joshi et al., 2021).

Among the many influences on ENSO teleconnections towards the NAE region, the Tropical North Atlantic (TNA) influence remains unclear both in terms of the underlying mechanism, as well as the timing of the influence. The TNA region is salient
30 for its strong connection to ENSO, whereby TNA SST anomalies (SSTA) are positively correlated with the Niño3.4 index and peak in boreal spring (March-May, MAM) following an ENSO event (Enfield and Mayer, 1997; Lee et al., 2008). This robust teleconnection travels through both a tropical and an extratropical pathway, influencing the TNA SSTs through either moist convection/stability processes or changes in the trade winds (Jiang and Li, 2019; Casselman et al., 2021). There is also a connection between the TNA and NAE region. This connection includes the propagation of Rossby waves that can contribute
35 to a circumglobal wave train (Toniazzo and Scaife, 2006; García-Serrano et al., 2011; Saeed et al., 2014; Scaife et al., 2017; Matsumura and Kosaka, 2019), as well as changes in the Hadley cell and Inter-Tropical Convergence Zone (ITCZ) (Okumura et al., 2001; Michel and Rivière, 2011). The resulting wave train can project onto different summertime circulation regimes over the NAE region, such as the Atlantic low (Cassou et al., 2005).

The neighbouring Caribbean region also plays a role in the excitation and propagation of Rossby waves to the extratropics
40 (Wulff et al., 2017; Hardiman et al., 2019; Neddermann et al., 2019; Rieke et al., 2021). In particular, Rossby wave trains originating in the Caribbean region can influence the Summer East Atlantic (SEA) pattern, impacting European summer climate (Wulff et al., 2017). A proposed forcing for this wave train includes opposing diabatic heating anomalies over the tropical Pacific and Caribbean, referred to as the Pacific-Caribbean Dipole (PCD). **Here**, the PCD is related to SSTAs between June and August (JJA), occurring during the developing phase of an ENSO event. In addition to influencing the regional climate over
45 Europe, a wave train launched from the tropical **Atlantic or Caribbean** can continue as far downstream as Southwestern China, including an influence on rainfall and the East Asian summer monsoon (Li et al., 2018; Choi and Ahn, 2019). Often referred to as the East Atlantic/ West Russia (EA/ WR) teleconnection, this teleconnection shows potential for skillful prediction in all four seasons (Lledó et al., 2020). Furthermore, since the EA/WR teleconnection may result from a westward extension of the downward branch of the Pacific Walker cell, and a Gill response over the eastern equatorial Pacific, the EA/WR teleconnection
50 may relate to the PCD index (Lim, 2015; Choi and Ahn, 2019).

It is clear that the Caribbean region and the associated PCD mechanism could create meaningful impacts on interannual timescales not just in the NAE region, but also eastwards of the NAE region. However, it remains unclear why the PCD and Caribbean Rossby Wave Source (RWS) are more related to the developing phase of an ENSO event. The precipitation dipole corresponds to an SST gradient, whereby the RWS intensifies when the Pacific and Atlantic basins have opposing SSTAs (Wulff
55 et al., 2017). As the PCD index locations also correspond well with the regional edges of the Pacific and Atlantic Walker cells, the precipitation dipole is also likely related to the climatological upwelling and downwelling branches of the two adjacent Walker cells, which can be influenced by underlying SSTs. Furthermore, since there is a co-variance between the Pacific and Atlantic SSTAs (Casselman et al., 2021), i.e. the basins often have anomalous SSTAs of the same sign, the role of the TNA for influencing the PCD following an ENSO event may be important. Specifically, it could be hypothesized that the positive

60 correlation between ENSO and the TNA SSTA may explain why the PCD is reduced/not active during the decaying phase of an ENSO event, as an intensifying TNA SSTA in boreal spring reduces the overall SSTA gradient between the basins.

The positive correlation between the Pacific and Atlantic SSTAs also results in key atmospheric differences related to different **Matsuno Gill**-type responses (hereafter shortened to Gill type response). In response to anomalously positive SSTAs and diabatic heating over the equatorial Pacific, tropical wave theory predicts that the atmosphere will be perturbed by creating a pair of symmetric upper-level anticyclones (Gill, 1980; Lee et al., 2009). Downstream, the Walker cell is also perturbed via Kelvin wave propagation from the initial Gill type response, resulting in a Secondary Gill response. This response is opposite to the initial perturbation, creating descending motion and a pair of upper-level cyclones over South America (García-Serrano et al., 2017; Casselman et al., 2021). Likewise, as the tropical Atlantic also tends to have a positive SSTA preceding an ENSO event, an atmospheric Gill-type response is created, including a pair of upper-level anticyclones. However, given the nature of the tropical Atlantic SSTA (i.e., SSTAs predominantly occur north of the equator), the Northern Hemisphere exhibits an enhanced response, leading to an asymmetric Gill type response (Gill, 1980). Thus there is potentially a counteracting atmospheric response between the Secondary Gill response from an El Niño, and the asymmetric response created from the TNA SSTA.

However, when determining how ENSO teleconnections interact with different regions, a major issue for isolating influences onto ENSO teleconnection is the limited number of observed events in reanalysis datasets. As a result, several studies have turned to model experiments to generate further events. Nevertheless, coupled models also have their own set of difficulties in representing ENSO variability correctly (i.e., SST diversity and strength), which is essential in recreating ENSO teleconnections properly (Frauen et al., 2014; Bayr et al., 2019). One solution to this problem is to prescribe realistic SSTs in an Atmospheric General Circulation Model (AGCM). By using an AGCM to isolate the influence from the TNA, this study aims to determine if the TNA modulates the influence on the ENSO teleconnection towards the NAE region. We consider the interactions between the tropical basins, as well as interactions between the tropics and the North Atlantic **during boreal spring and summer**. We consider the differences between forcing the two basins simultaneously or separately to determine the linearity of the response and the areas where the Atlantic response acts constructively or destructively on the ENSO teleconnection towards the North Atlantic. **While ENSO teleconnections towards the North Atlantic can travel through either the stratosphere or troposphere (Jiménez-Esteve and Domeisen, 2018), teleconnections that travel through the Caribbean are tropospheric (Hardiman et al., 2019), and hence our study focuses on the tropospheric pathway only.**

2 Methodology

2.1 Data

This study utilizes monthly mean SST from the Extended Reconstructed Sea Surface Temperature (ERSST) version 4 (Huang et al., 2015), as well as monthly mean fields (zonal/meridional winds, geopotential height, and precipitation) from the Japanese 55-year Reanalysis (JRA-55) (Kobayashi et al., 2015). We analyze the period from January 1958 until December 2019. We use a 30-year filter to remove low-frequency variability longer than 30 years for all fields, created using a fast Fourier transform

(FFT). Statistical significance is calculated using a Monte Carlo test that is repeated 10,000 times to determine the significance of the atmospheric response (Buckland and Noreen, 1990). This test selects a number of samples based on a given subsampling criterion, and compares the distribution to either the population from which the samples were drawn (as in reanalysis), or for the comparison of different model runs. **We also use correlation (R) throughout, and derive significance by using a confidence interval created by using a Fisher transform (Devore, 1991; Simpson and Polvani, 2016).**

2.2 Model Description and Experiments

In addition to reanalysis data, we utilize Isca (Vallis et al., 2018), a simplified atmospheric general circulation model (AGCM), to conduct a series of targeted forcing experiments. This model uses the Geophysical Fluid Dynamics Laboratory (GFDL) dynamical core, and uses the same model configuration as Jiménez-Esteve and Domeisen (2020). The atmosphere does not have explicit liquid water content but instead the moisture and radiative processes are considered using evaporation from the surface and a fast condensation scheme. Land-sea contrasts are created by changing the mixed layer depth, evaporative resistance, and albedo, while realistic topography is achieved by using the continental outline from ECMWF (Thomson and Vallis, 2018a, b). Finally, the model resolution includes a Gaussian grid with 50 vertical levels (up to 0.02 hPa) and T42 horizontal resolution.

We perform three different model experiments, along with a control run. The climatological SST forcing is created using the ERSSTv4 climatology from 1958-2019. In addition to the climatological SSTs, we perform experiments including a Pacific-only (ENSO-like, ‘P’) forcing, Atlantic-only (TNA SST following an ENSO event, ‘A’) forcing, and a combined Pacific-Atlantic forcing, where SSTAs in both basins are forced (‘AP’). Over the forced regions, the SST forcing is derived by regressing the Niño3.4 index onto the SSTA field, which is then added to the background climatology. We choose to include both positive and negative SSTAs as previous studies have shown that the zonal SSTA gradient is important for influencing the Walker circulation (Zhao et al., 2021). The SST forcing is computed by regressing the October to February (ONDJF) mean Niño3.4 index onto the monthly SST field, backwards to August and forward to the following October. August to October of both the backward and forward regressions are averaged to create a smooth annual cycle. Similar to Jiménez-Esteve and Domeisen (2020), regression values are multiplied by 4, resulting in an SSTA peak of approximately 4°C in the Pacific, and a peak of approximately 1°C in the Atlantic (for DJF and MAM, respectively, see Figure 1 for forcing pattern and annual cycle). We chose to multiply the forcing by 4 to ensure a **sufficient amplitude of the** response, but it should be acknowledged that this forcing is stronger than in observations. **Furthermore, the atmospheric response to the SSTA forcing may exhibit nonlinearities (i.e., the upper-level divergence responds nonlinearly to a linear change in the magnitude of Pacific SSTAs), but given our analysis is during boreal spring and summer when Pacific SSTAs are weaker than in boreal winter, any nonlinearities may also be weaker than those during boreal winter (Graham and Barnett, 1987; Sabin et al., 2013).** Finally, for this study, we aim to determine the importance of the TNA following an El Niño only, and we do not consider La Niña events.

The forcing region for the Pacific spans from the coastline of the Americas to 124°E, with a linear decrease to climatology from 124°E to 114°E. Similarly, in the meridional direction the forcing linearly decreases to zero between 14°N-24°N and

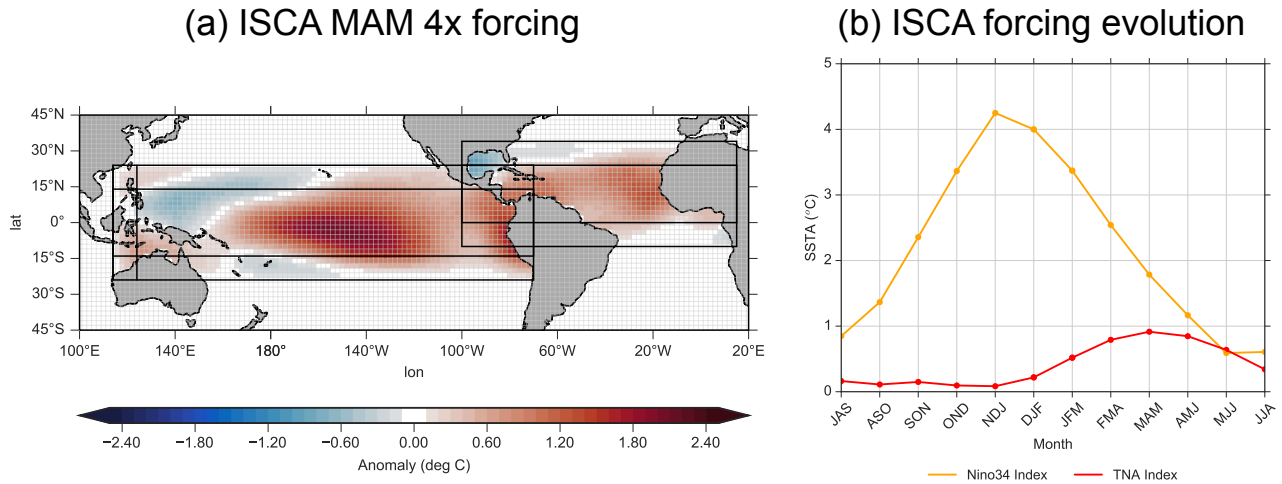


Figure 1. Forcing areas and seasonal evolution used to force ISCA. (a) depicts March-May (MAM) SST forcing for the AP runs (combined Pacific and Atlantic forcing). Black outlines indicate areas where regression was used, with outside rectangles indicating transition areas of linear decrease (see S1 for percentages). (b) shows the seasonal evolution of Niño3.4 (orange) and TNA (red) indices using a 3-month running mean.

14°S–24°S. The Atlantic forcing spans the area from the African coast to the Americas. Since the dominant SSTA following an ENSO event is located in the northern part of the tropical Atlantic (peaking around 15°N), we use a linear decrease to zero from 0 to 10°S, and from 24°N to 34°N (Czaja et al., 2002).

130 Climatological runs are forced with monthly SSTs averaged between 1958–2019. There are 50 years with a recurrent SST seasonal cycle, of which the first 20 years are removed as spin-up. The forced SST experiments (P, A, AP) continue from the twentieth year of climatology for another 60 years. Removing the first year for spin up yields 59 years in total for each forced SST simulation. In order to compute the streamfunction and perform a Helmholtz-decomposition, missing values of the model experiments are filled solving Poisson’s equation with a tolerance of 10^{-4} , relaxation constant of 0.6, and an iteration

135 maximum of 89.

To remove the potential indirect influence from stratospheric variability, we relax (nudge) the zonal mean of the zonal winds above the tropopause to the daily climatology of the control simulation as in Jiménez-Esteve and Domeisen (2020). The relaxation term is computed at each model timestep and applied to the zonal mean zonal wind temporal tendency. Nudging is applied for pressure levels above 0.2 times the tropopause level and includes a transition layer between 0.5 and 0.2 times the

140 tropopause pressure level. See Jiménez-Esteve and Domeisen (2020) for the mathematical description.

2.3 Statistical Methods

We use multiple linear regression (MLR) analysis to isolate the linear influence from the Atlantic and Pacific, respectively, and plot the pointwise MLR coefficients following the method in Izumo et al. (2010) and Casselman et al. (2021). We also utilize partial correlation between three variables, following Wang et al. (2006). The partial correlation between variables X and Y ,
 145 when removing the influence of variable Z , is calculated as follows:

$$R_{XY/Z} = \frac{R_{XY} - R_{YZ}R_{XZ}}{\sqrt{1 - R_{YZ}^2}\sqrt{1 - R_{XZ}^2}}, \quad (1)$$

where R_{XY} represents the linear correlation coefficient between X and Y .

2.4 Index Definitions and Diagnostics

To evaluate Pacific SSTA, we use detrended 3-month running averages of SSTs averaged over the equatorial Pacific region
 150 bounded by 5°N - 5°S , 170°W - 120°W . The TNA index is defined as the area-averaged SST over the region of 5°N - 25°N , 55°W - 15°W , as in Taschetto et al. (2016). Finally, we utilize the Pacific-Caribbean Dipole (PCD) index as defined by Wulff et al. (2017). This index is determined by the normalized area-averaged precipitation difference between the Pacific and Caribbean (Pacific box [10°N - 20°N , 180° - 110°W] minus Caribbean box [10°N - 25°N , 85°W - 65°W]).

To analyze the upper-level circulation, we compute the streamfunction equation in Cartesian coordinates by using spherical
 155 harmonics (Dawson, 2016). This includes $u = \delta\psi/\delta y$ and $v = -\delta\psi/\delta x$, where ψ represents the streamfunction, and $u(v)$ are the zonal (meridional) winds. The zonal mass streamfunction over the equatorial region is calculated analogously to the meridional mass streamfunction, except with a longitudinal and not latitudinal dependence, and we use the mean of winds between 5°N to 5°S . Furthermore, we utilize the Helmholtz-decomposed zonal divergence (u_χ) for the streamfunction equation, under the assumption that the circulation is primarily thermally driven between 5°N to 5°S (Yu et al., 2012). The zonal stream
 160 function (Ψ_z) is defined as:

$$\Psi_z = \frac{2\pi a}{g} \int_0^p [u_\chi]_{5^\circ\text{N}}^{5^\circ\text{S}} dp, \quad (2)$$

where a is the Earth's radius, g is gravitational acceleration, p is pressure, and the brackets indicate the latitude for integration. An index measuring the Walker cell gradient between the Pacific and Atlantic, the *Walker index*, is defined as the upper level (200-400 hPa) streamfunction **in the Atlantic (5°N - 5°S , 310° - 340°W) minus the streamfunction in the Pacific (5°N - 5°S ,
 165 240° - 270°W).**

The Rossby wave source (RWS) (Sardeshmukh and Hoskins, 1988) is defined as:

$$RWS = -(\zeta \nabla v_x + v_x \nabla \zeta), \quad (3)$$

where ζ is the absolute vorticity, and v_x is the divergent meridional wind. The first term represents vortex stretching, while the second represents vorticity advection. Furthermore, a Gaussian smoothing with a Gaussian kernel standard deviation of 0.7

170 is applied to be able to interpret the large-scale responses. A localized *Caribbean RWS index* is defined as the area average of the 200 hPa RWS field bounded by 5-15°N, 80-60°W.

In the North Atlantic, we define the NAO using the index by Li and Wang (2003), which measures the difference between the zonally averaged SLP at 35°N and 65°N from 80°W to 30°E. We define the East Atlantic pattern as an area average of the 500 hPa geopotential height between 40-60°N, 310-340°E (see Supplementary Figure S2). We chose this
175 definition over an EOF as the dominant modes of variability change between the different model experiments.

3 Results

3.1 Inter-Basin Relationship Between Equatorial Atlantic and Pacific in Reanalysis

We begin by comparing the different impacts from both the Pacific and Atlantic SSTAs onto the upper level circulation over equatorial South America and the Atlantic by applying an MLR analysis to the JRA-55 reanalysis dataset. Specifically, we aim
180 to identify the respective influences each equatorial region may have on the Walker circulation. Understanding this interplay is salient as the combined influence over South America and the Caribbean region may be crucial for creating an RWS that can propagate a Rossby wave train that influences the extratropics. The MLR analysis allows for an approximate separation of the influences from the respective equatorial basins, which is necessary since ENSO and the TNA SSTA co-vary to a high degree. Finally, we focus on boreal spring and boreal summer for all fields as we are interested in the impact the TNA SSTA peak has
185 following an ENSO event (MAM, Casselman et al. (2021)), as well as the time period when the Atlantic warm pool has the largest influence onto the Walker circulation (JJA)(Wang et al., 2006, 2010; Rojo Hernández and Mesa, 2020). Both MAM and JJA are also related to wave trains towards the NAE region (Lim, 2015; Jung et al., 2017; Wulff et al., 2017; Li et al., 2018; Choi and Ahn, 2019; Neddermann et al., 2019; Lledó et al., 2020).

To better understand how each equatorial basin influences the vertical winds (associated with differing Gill type responses)
190 over South America and the Caribbean, we show the boreal spring and summer Walker cells using an MLR with the zonal mass streamfunction and winds between 5°N and 5°S (Figure 2), in reference to the DJF Niño3.4 (preceding year) and MAM TNA (same year) indices. Anomalous Walker cell streamfunction and wind vectors for boreal spring and summer indicate that the influence from the Atlantic and Pacific SSTAs counteract one another during both boreal spring and summer. In boreal spring (Figure 2a-b) this counteraction includes strong upper level divergence over the eastern Pacific (associated with
195 a weakening El Niño event), strong westerlies over South America, and descending motion around the western Atlantic. Conversely, Atlantic SSTAs are associated with divergence over the western Atlantic, and strong upper level easterlies over South America, consistent with Wang (2002). Notably, over South America and the western Atlantic there is counteracting descending and ascending anomalies associated with the Pacific and Atlantic SSTAs, respectively.

During boreal summer, anomalies related to both the TNA and ENSO largely continue from boreal spring, except that the
200 upper level divergence due to Atlantic SSTAs has reduced, and vertical motion over South America has changed, whereby there is now descending motion around around the western Atlantic. As a result, shifting from boreal spring to boreal summer shows a shift from destructive vertical motion to constructive vertical motion over the western Atlantic and parts of eastern

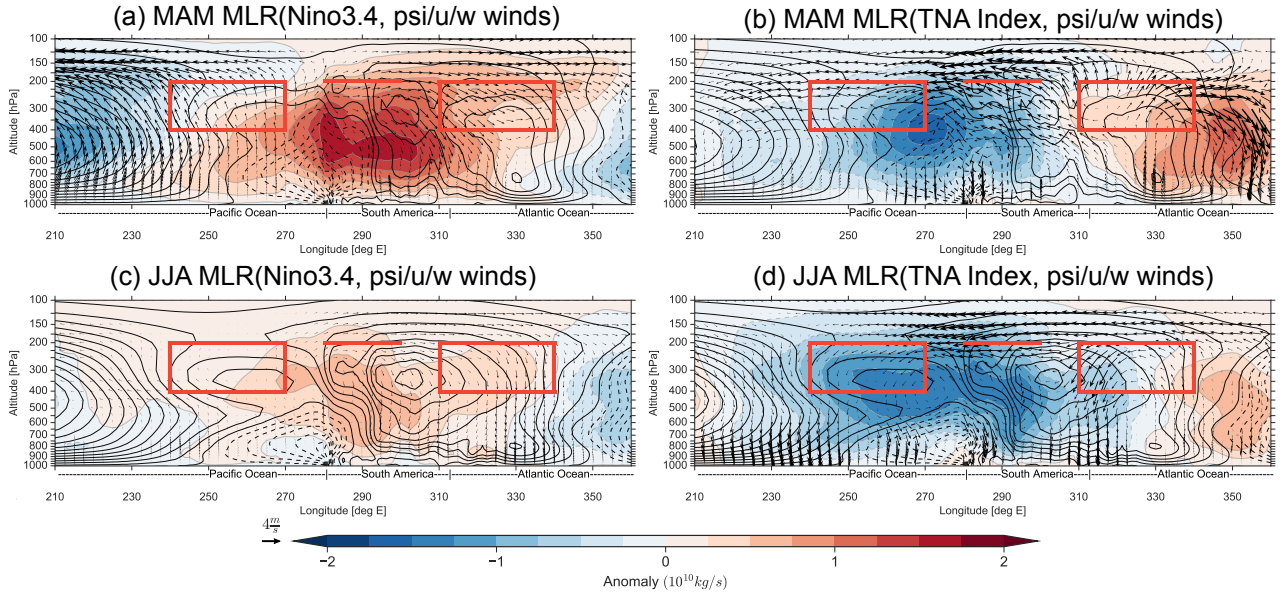


Figure 2. Pointwise multiple linear regression coefficients for the MAM (top) and JJA (bottom) zonal mass streamfunction (shading) and u and w winds components (vectors) on the MAM TNA SSTa and DJF Niño3.4 standardized indices. Contours represent the zonal mass streamfunction climatology (in intervals of 1.5×10^{10} kg/s), and winds are scaled by dividing the vertical velocity by 6.5×10^{-3} . Red rectangles over the Pacific and Atlantic represent the Walker index, while the horizontal line at $290^\circ E$ represents the Caribbean RWS index. Data from JRA-55.

South America, while over central and western South America the result continues to show destructive interactions. As boreal summer streamfunction anomalies are much higher from the Atlantic forcing when compared to the Pacific, the Atlantic likely dominates the Walker cell perturbation. In contrast, in boreal spring, both basins perturb the Walker cell to a similar degree.

Thus, we find that there are counteracting upper level winds over South America as a result of the different forcings from the Atlantic and Pacific basins. Furthermore, vertical motion over South America and the Caribbean depends on the respective strength of the Atlantic and Pacific Walker cells, as this region sits at the boundary between both. This dependence on both cells may help explain why Wulff et al. (2017) could characterize the **PCD and resulting RWS** over this region with a dipole index. As they also found that the precipitation field can be replaced by SSTs, this further indicates that both ocean basins play an important role in driving the PCD.

3.2 Lead-lag Relationships of Major Tropical Connections in Reanalysis

As we are interested in the respective influences from each equatorial basin onto the Walker cell, and the resulting upper level RWS over the Caribbean, we next create a large-scale streamfunction gradient index between the Pacific and Atlantic, centered over the Caribbean. We complement this index with a more localized RWS index over the Caribbean. We use a 24-

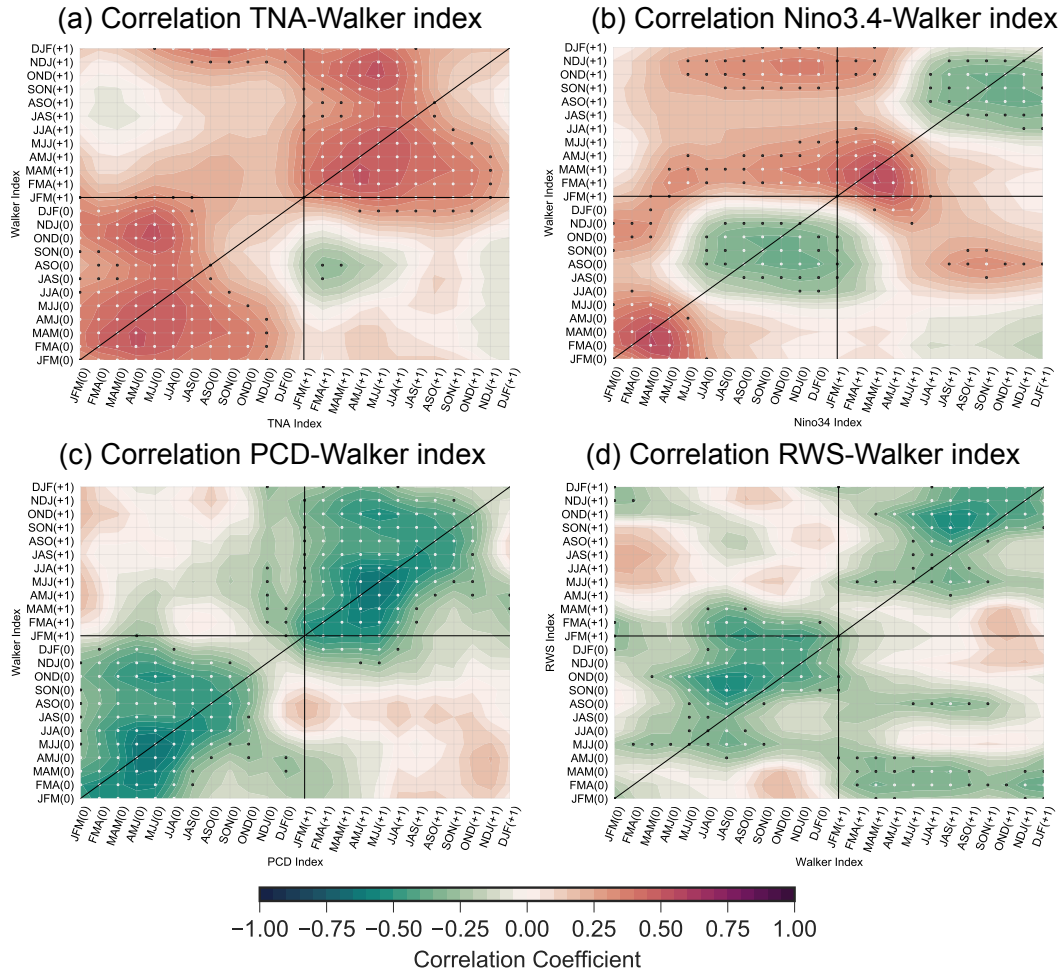


Figure 3. Lead-lag correlation between (a) the Walker index and TNA, (b) the Walker and Niño3.4 indices, (c) the Walker and PCD indices, and (d) the Walker and Caribbean RWS indices. The ‘(0)’ and ‘(+1)’ refer to the starting year or subsequent year for each index, the diagonal line corresponds to no lag, and values above (below) the diagonal line represent a lead (lag) of the x-axis variable. The black dots represent the 95% confidence interval, and white dots represent the 99% confidence interval. Results are using data from JRA-55 only.

month lead/lag correlation analysis to analyze the Walker cell relationships, and to further understand how connections with ENSO and the TNA change between MAM and JJA. Figure 3 shows the lead/lag correlation of the Walker index (upper-level streamfunction gradient between Pacific and Atlantic) with the TNA, Niño3.4, PCD (precipitation dipole between Pacific and Atlantic), and the Caribbean RWS indices. We compare the PCD to the Walker cell gradient, as it is hypothesized that both mechanisms are highly related. The correlation between the TNA and the Walker index (Figure 3a) is positive, peaking in boreal spring at a significance level >99%. Furthermore, the April-June (AMJ) to JJA TNA SSTA continues to influence the Walker index at the 99% level into the following boreal winter (DJF, 8 month lead). Similarly, the

relationship between the Walker index and Pacific SSTA (Figure 3b) is positive and peaks in the following boreal spring, but becomes $>99\%$ significant with a **six** season lead for the Niño3.4 index (SON of previous year). The relationship between the Walker index and peak of ENSO (boreal winter Niño 3.4) drops off rapidly after boreal spring, while the relationship with the peak of TNA SSTA continues until the following boreal winter. This indicates that the TNA SSTA dominates the Walker cell influence in boreal summer, when compared to ENSO, and is consistent with the previous MLR analysis. This relationship with the DJF Niño3.4 and Walker index also remains when using the boreal spring Niño3.4 (same season as TNA peak, MAM), as well as when considering a 0 lag correlation.

The boreal summer Walker index also has a negative correlation with the preceding ENSO event (Figure 3b), similar in timing (but opposite in sign, as the PCD and walker index dipoles are reversed) to the relationship found by Wulff et al. (2017) for the PCD-ENSO relationship. This hints at the similarities between the Walker and PCD indices. Thus, we further correlate the Walker and PCD indices (Figure 3c), showing that their relationship is significant above the 99% level for all seasons, with the exception of early boreal winter. The peak correlation occurs in boreal spring with a lead/lag of 0. As the relationship is continuous over most seasons and the indices measure similar aspects, the Walker cell and PCD index may be either highly coupled, or represent the same phenomenon. **Furthermore, as the Walker cell gradient and PCD are highly coupled, for the remainder of this paper, we use only the Walker cell gradient.** Finally, we relate the Walker index to the more localized Caribbean RWS index (Figure 3d), which yields a similar relationship as the PCD index, with a negative correlation that is $>95\%$ significant during all seasons except in late boreal winter **and spring**.

240 3.3 Tropical Pacific and Atlantic Interactions In ISCA

Up to this point, we applied an MLR to reanalysis data to determine the relationship between the Pacific and Atlantic SSTs with the Walker circulation. This is useful for showing that both basins play important roles, and also that the importance may shift between boreal spring and summer. **However, this method cannot fully capture the nonlinear contribution, as it assumes that the effects from each basin onto the Walker cell are additive** (Osborne and Waters, 2003), which is likely not true. Due to the limited data in reanalysis and the high degree of correlation between ENSO and the TNA, it is also difficult to perform targeted experiments by subsampling based on whether the signal in the TNA SSTA is present following an ENSO event. To overcome these issues and to further test our MLR findings, we isolate the influences from the equatorial Pacific and Atlantic using the atmospheric model *Isca* with a series of targeted experiments.

In order to **address the sensitivity of ENSO to the TNA SSTAs**, we determine the **separate** and combined influence of both basins **using** separate forcings for the Atlantic (A), Pacific (P), as well as both basins forced simultaneously, (i.e. Atlantic+Pacific (AP)). **To determine the linearity of ENSO's response to the addition of the Atlantic SSTAs**, we also look at the linear addition ($A + P$) of the responses from each basin in comparison to the simultaneous forcing (AP), and calculate the difference between forcing each region simultaneously or separately ($AP - (A + P)$). Finally, we also compare forcing an El Niño event that includes the Atlantic SSTA in the subsequent boreal spring to forcing the Pacific only ($AP - P$), thus isolating the Atlantic influence that often follows an El Niño event. It should be noted that this change should not be

interpreted as the Atlantic response only (look to A for this), but instead as the difference between AP and P , as differences in the Pacific response may occur alongside the Atlantic response.

We consider the Walker cell between 5°N and 5°S , as in reanalysis, to determine the salience of the positive Atlantic SSTA, and its influence on the teleconnections arising from an El Niño event. Isca reproduces a realistic climatology (lined
260 contours in Figures 2 and 4), which includes strong clockwise (positive) cells over the central Pacific and Atlantic, and a small counter-clockwise (negative) cell over the eastern Pacific. Notably, however, the boundary directly above South America is more disordered when compared to JRA-55 (contours in Figure 2). This difference to reanalysis over South America may result from a poor representation of the low level flow over the Andes mountain range (i.e. a low level Kelvin wave response) due to the comparably coarse model resolution (Rojo Hernández and Mesa, 2020).

265 The model experiments for boreal spring show that the Atlantic forcing A (Figure 4a) creates a response similar to the JRA-55 MLR analysis, including strong ascending motion over the Atlantic, strong upper level easterlies over South America, and a large-scale counter-clockwise streamfunction anomaly. Also similar to our MLR analysis, the response to Pacific forcing P (Figure 4b) creates divergence over the eastern Pacific, descending motion over South America and the western Atlantic (Secondary Gill response), but lacks the strong upper level westerlies seen in the MLR analysis (Figure 2a). When forcing both
270 basins simultaneously (AP , Figure 4c), the large-scale streamfunction response matches the pattern when forcing the Pacific only (P), which includes a strong clockwise anomaly over South America and counter-clockwise anomalies over the Pacific and Atlantic. Thus, this similarity indicates that the Pacific remains the dominant influence onto the Walker cell during boreal spring for our model experiments, and that the Secondary Gill response from an El Niño likely dominates over the asymmetric Gill response from the positive Atlantic SSTA. However, it should be noted that the Atlantic SSTAs do create a noticeable
275 increase in upper level westerlies over South America, and strengthen the counter-clockwise streamfunction response over the eastern Pacific.

Forcing the Pacific and Atlantic SSTs both simultaneously and separately (Figure 4c-d) yields a very similar response, indicating a high linearity between the responses. Both AP and $A+P$ show an intensification of the upper level westerlies over South America when compared to P . Further comparing AP and $A+P$ (Figure 4e) shows that wind anomalies are nearly
280 identical and that much of the streamfunction differences over South America are not statistically different. Finally, we compare responses from forcing an El Niño only, with forcing an El Niño and Atlantic SSTA ($AP-P$, Figure 4f) and find that the difference closely resembles the A response. **Furthermore, AP and P are statistically different throughout much of the tropical basin (stippling in Figure 4f).** As the streamfunction over South America is not statistically different between $AP-P$ and A (Figure S3), this further shows that during boreal spring, the influence from the Atlantic SSTA linearly interacts with
285 the influence that an El Niño event has with the Walker cell.

As we are also interested in how the influence shifts from boreal spring to boreal summer, Figure 5 shows the Walker cell response to our model experiments for JJA. For A (Figure 5a), the response for boreal summer compared to boreal spring shows similar upper level westerlies that extend into the Pacific, showing descending motion over parts of South America, consistent with our MLR analysis. At the same time, the response to P (Figure 5b) largely lacks significant descending motion over South
290 America, showing that the Secondary Gill response has likely subsided.

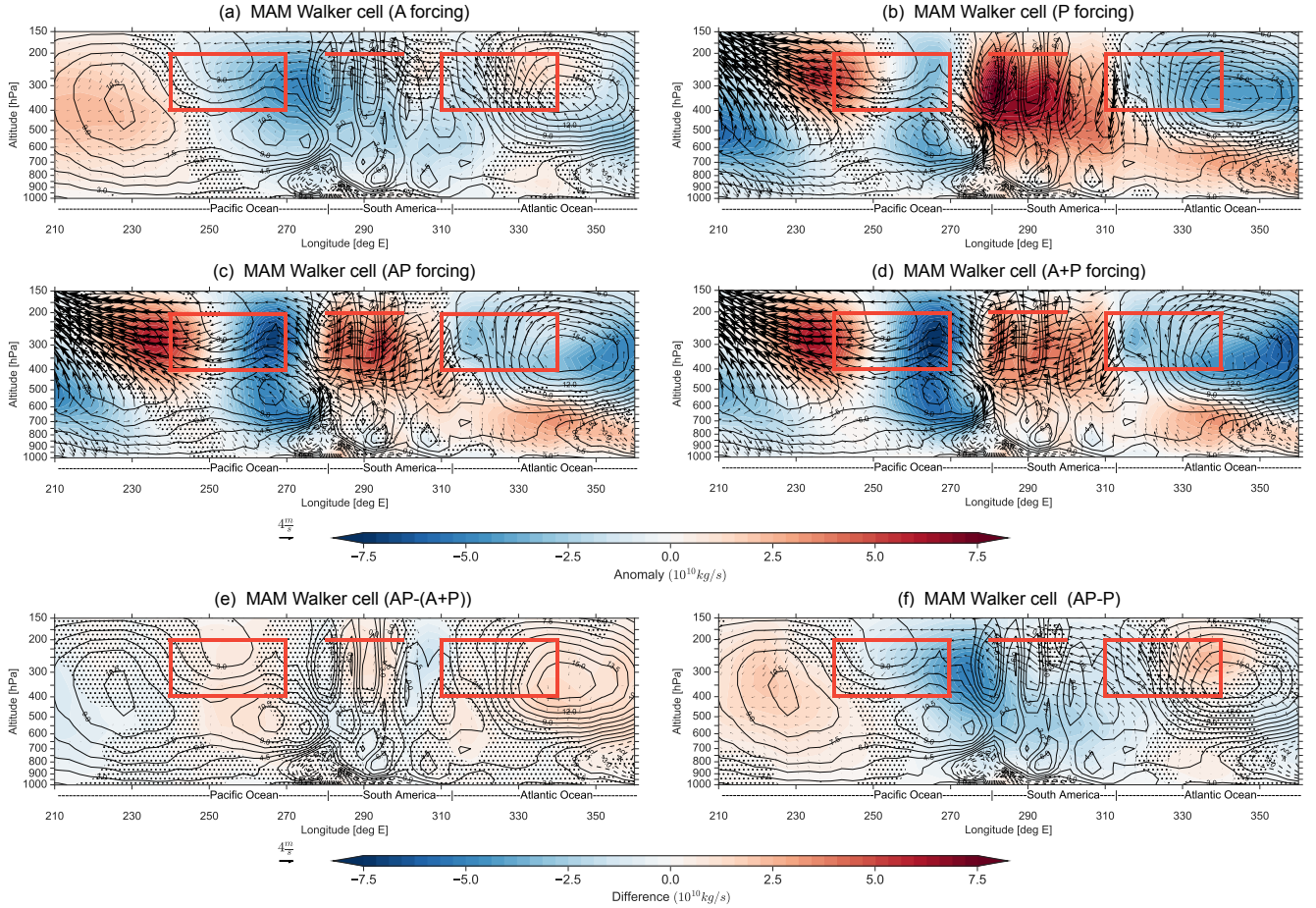


Figure 4. MAM Walker Cell analysis for the region connecting the Pacific and the Atlantic, averaged between 5°S and 5°N . Shading represents the streamfunction (ψ), contours represent the streamfunction climatology (in intervals of $1.5 \times 10^{10} \text{ kg/s}$), and vectors represent the zonal winds (u), and vertical velocity (w) response to the different forcings from the Atlantic (a), Pacific (b), and Atlantic+Pacific combined (c), as well as the linear addition of the Pacific and Atlantic contributions (a+b). The contours represent the model climatology. **The difference between the linearly combined response (A+P) and the combined response (AP simultaneously) is represented in (e), while the Atlantic contribution (f) is derived as the difference between (c, AP forcing) and (b, P forcing).** Stippling in (a-c) represents anomalies that are not statistically significantly different from climatology at the 95% level using a two-tailed Monte Carlo test. Stippling in (e) represents differences that are not statistically significantly different between the AP forcing (c) run and the linear combination of the Atlantic and Pacific (A+P, Figure d), at the 95% level using a two-tailed Monte Carlo test. Stippling in (f) represents differences that are not statistically significantly different from the P forcing run at the 95% level using a two-tailed Monte Carlo test. The rectangular boxes represent the areas for computing the Walker index, while horizontal line represents level and longitude for RWS index. **Wind vectors in e and f represent statistically different winds from (A+P) and (P), respectively.**

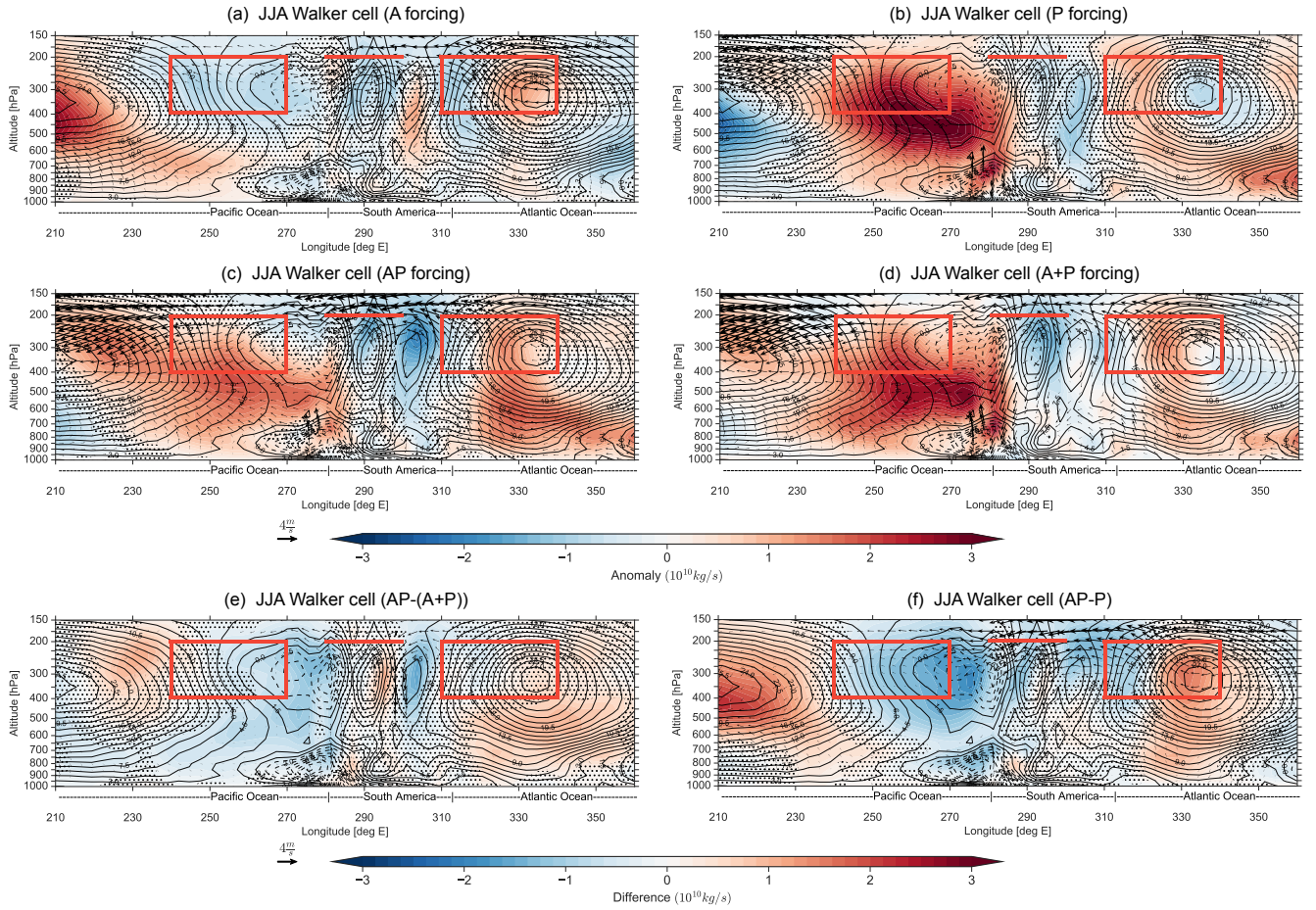


Figure 5. Same as Figure 4, but for JJA.

When forcing the regions simultaneously (*AP*, Figure 5c) and comparing to *P* (Figure 5f), the Pacific streamfunction response is weakened, while the South American streamfunction response is strengthened, corresponding well with the constructive/destructive areas in *A* and *P* (Figure 5a-b). *A+P* (Figure 5d) also shows that the linear addition of each basin's influence results in a much stronger Pacific streamfunction response when compared to *AP* (Figure 5c), indicating that the Atlantic forcing may weaken the Pacific contribution over the Pacific. The difference between the simultaneous and separate forcing (*AP-(A+P)*, Figure 5e) also shows statistically significant differences in the streamfunction response over the Pacific, while the upper level wind response is much more linear.

To expand on the influence from adding the Atlantic SSTA, Figure 5f shows the difference between forcing an El Niño event with and without the Atlantic forcing (*AP-P*). Furthermore, similar to boreal spring, *AP* and *P* are statistically different throughout much of the tropical basin (stippling in Figure 5f). Results also show a spatially similar, but significantly stronger streamfunction response when compared to both the *A* response (Figure S3), as well as the *AP-(A+P)* difference.

This close resemblance in terms of spatial pattern potentially indicates that the nonlinearity arises from an intensified Atlantic influence, with respect to forcing the Atlantic independently. Overall, for the boreal summer, we find that the Atlantic contribution continues to dominate the upper level westerlies over South America and the overall streamfunction magnitude is **significantly** influenced by the Atlantic SSTA in both seasons. Furthermore, the nonlinearity likely arises from an intensified Atlantic response when coupled with the Pacific SSTA.

In addition to considering the Walker cell for understanding the competing Gill type responses (symmetric vs. asymmetric), we utilize the 200 hPa streamfunction. **As the Secondary Gill and asymmetric Gill type responses have distinct spatial patterns in streamfunction, composite analysis shows the inter-basin interaction from a different perspective than the Walker cells.** We again consider the same model experiments, and differences between responses to determine linearity. Beginning in boreal spring, the response to A (Figure 6a) shows an anti-cyclonic maximum over the Caribbean, and a dipole centered about the equator with a dominant northern section (asymmetric Gill response, consistent with Gill (1980)). Similarly, the response to P (Figure 6b) depicts a dipole over the deep tropical Atlantic consistent with García-Serrano et al. (2017), but the dipoles merge with the midlatitude response instead of forming distinct cyclones.

The response when forcing the Pacific and Atlantic simultaneously (AP , Figure 6c) shows a strong resemblance to the P response, but for AP the anti-cyclonic activity over the Caribbean (associated with the Atlantic SSTA) is intensified, and the Secondary Gill response from ENSO is more distinct from the midlatitude response. As little difference exists in comparison to the linear combination ($A+P$, Figure 6d), the symmetric and asymmetric Gill responses from each basin add linearly in boreal spring. Figure 6e further shows that there is little difference in the tropics between the simultaneously and separately forced responses ($AP - (A+P)$), since no clear spatial patterns occur that are statistically significant. The high linearity in this relationship can also be seen in Figure 6f, as the change in the response created by adding of the Atlantic forcing to an El Niño event closely resembles the tropical response from A , **and is statistically different from P** . However, this cannot be said for the extratropical response, which will be discussed in the forthcoming subsection.

Shifting to boreal summer, Figure 7 shows that the A and P responses (Figure 7a-b) result in generally opposite influences in the northern hemisphere, and that when combined in AP (Figure 7c), the asymmetric Gill response from the Atlantic dominates. By comparing the simultaneous and separate responses (AP vs. $A+P$), we see a nonlinearity arising, whereby the asymmetric Gill response is stronger in AP than in $A+P$ (also see Figure 7e). One potential reason for this change can be seen in Figure S4, which shows that the difference in response by adding the Atlantic SSTA forcing to an El Niño event is a stronger and more confined asymmetric Gill response over the Caribbean/South America than A . Overall, this nonlinearity in the tropics is consistent with the Walker analysis (Figures 4 and 5) where the inter-basin relationship shifts from linear to nonlinear from boreal spring to boreal summer. **As Figure 7f also shows statistically significant differences in equatorial zonal winds between AP and P , this** is also consistent with our lead-lag analysis showing that the dominant influence perturbing the Walker cell shifts from the Pacific to Atlantic SSTAs from boreal spring to summer. As $AP-P$ represents the overall result of adding the Atlantic SSTA, this nonlinearity may arise through an intensified Atlantic response in boreal summer, a weakened Pacific response, or a combination of both. However, given the spatial pattern matches the forcing from A , it is likely an intensified Atlantic response.

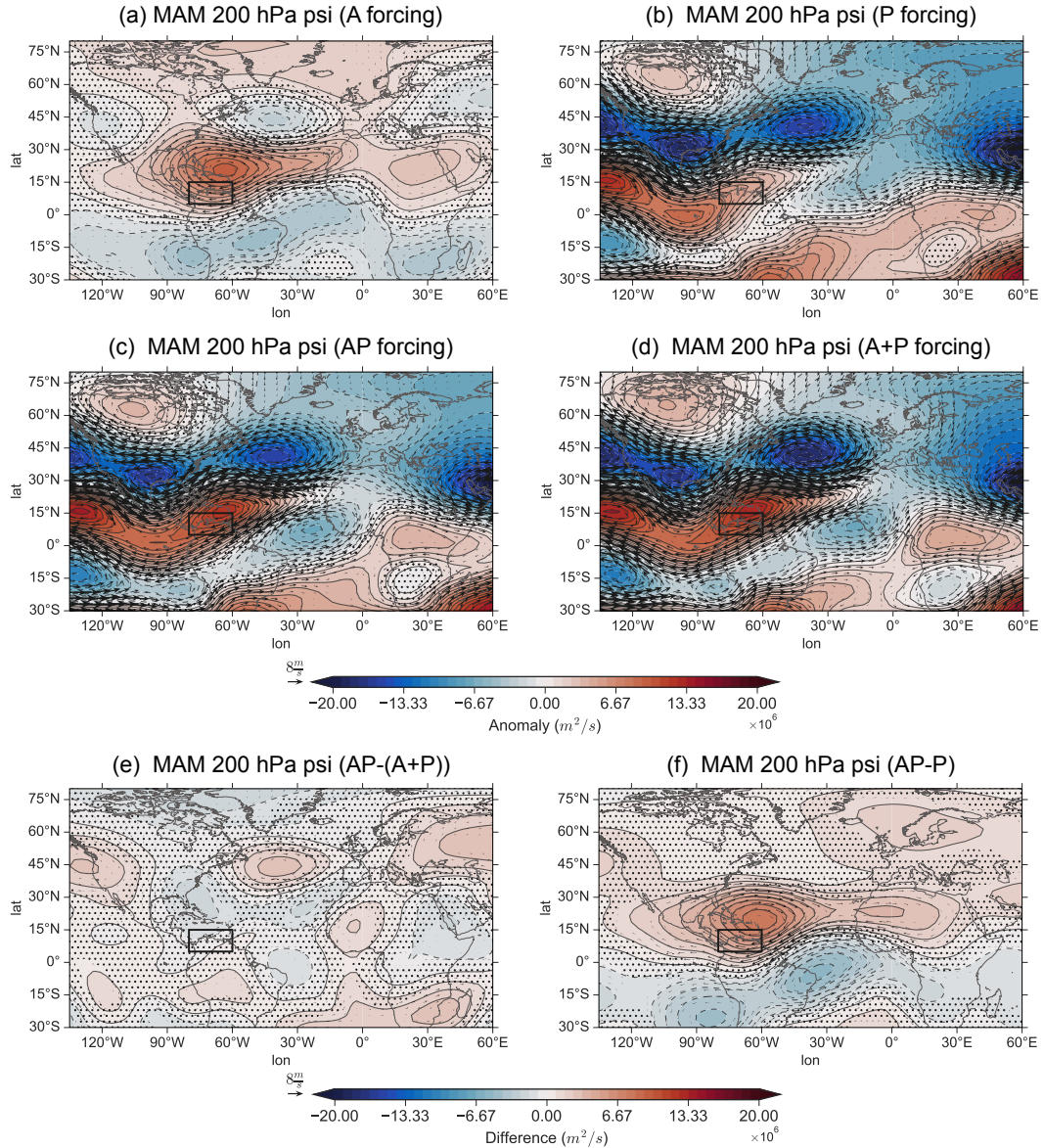


Figure 6. MAM 200 hPa streamfunction (shading) and non-divergent winds (vectors) analysis for the response to the different forcings from the Atlantic (a), Pacific (b), and Atlantic+Pacific combined (c), and linear addition of the Pacific and Atlantic contributions (a+b). **The difference between the linearly forced response (A+P) and the combined response (AP simultaneously) is represented in (e), while the Atlantic contribution (f) is derived as the difference between (c, AP forcing) and (b, P forcing).** Stippling in (a-c) represents anomalies that are not statistically significantly different from climatology, stippling in (e) represents differences that are not statistically significantly different between the AP forcing (c) run and the linear combination of the Atlantic and Pacific (A+P, Figure d), and stippling in (f) represents differences that are not statistically significantly different from the P forcing run, all at the 95% level using a two-tailed Monte Carlo test. Black box represents the RWS index over the Caribbean region. **Wind vectors in e and f represent statistically significantly different winds from (A+P) and (P), respectively.**

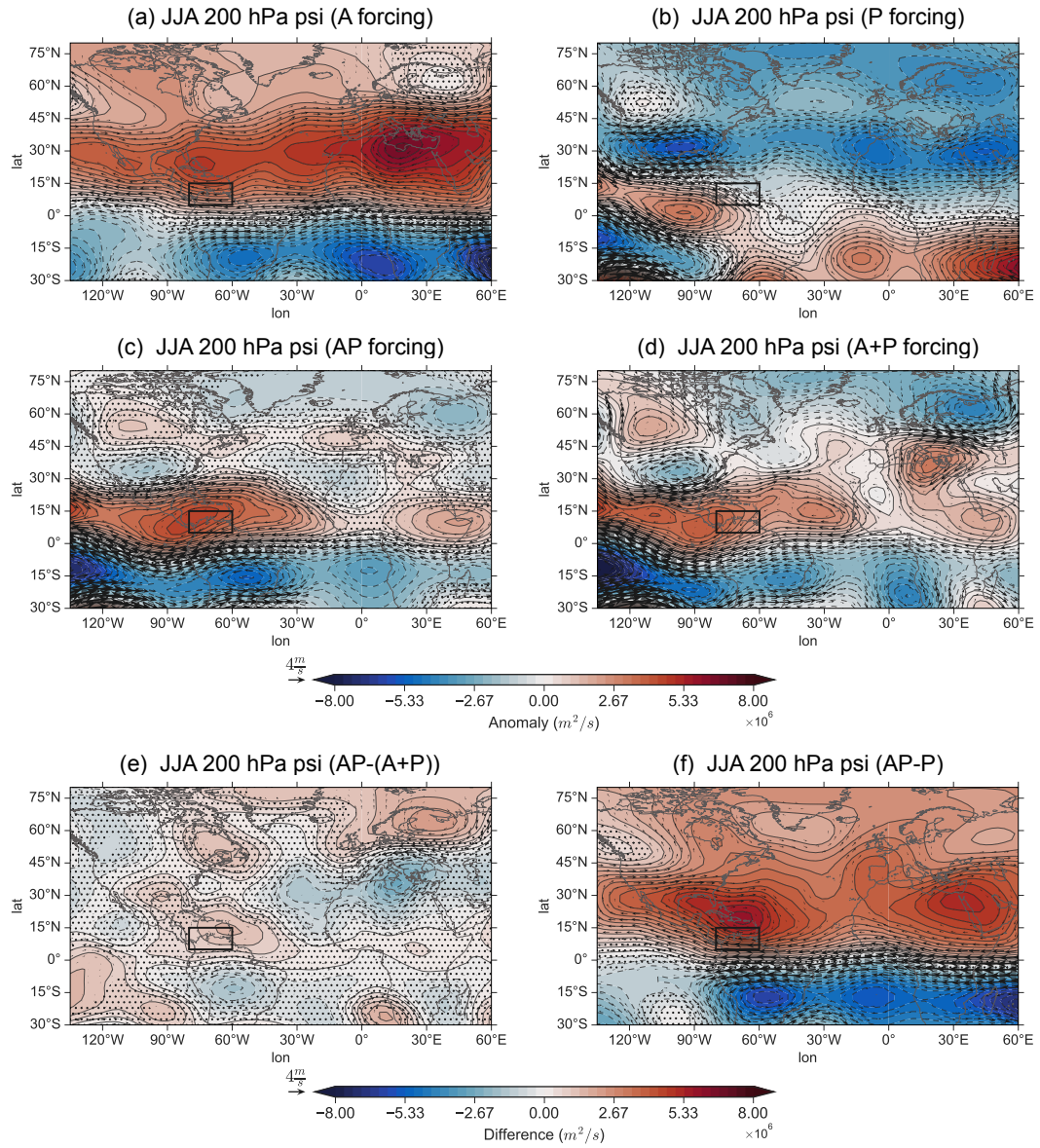


Figure 7. Same as Figure 6, but for JJA

3.4 Modulation of the tropical connection towards the North Atlantic-European Region by the Caribbean

Previously, the interaction between the tropical basins interested us as the combined influences may create a potential RWS, **or alter an RWS induced by the Pacific** that can influence the NAE region. As we now have a better idea of this inter-basin interaction, we next investigate how the Atlantic SSTA may influence the NAE region during an ENSO event via a Caribbean RWS. To do this, we quantify the aforementioned tropical interactions using the Caribbean RWS index and Walker index, while we use the East Atlantic (EA) pattern and North Atlantic Oscillation (NAO) to quantify the response in the NAE region. Consistent with previous sections, we again look at boreal spring and summer. **We use changes in both the correlation and mean anomaly between P and AP to quantify how sensitive ENSO's teleconnections are to Atlantic SSTAs.**

The Walker and Caribbean RWS indices have a strong relationship that varies considerably when applying the different SST forcings in boreal spring (Figure 8a). For P , the correlation is -0.28, while for A it is -0.33. When forcing both basins together (AP), the correlation increases by 57% to -0.44 as compared to only forcing the Pacific basin (P), **but we find that the difference is not statistically significant (see confidence intervals in Figure 8a). In boreal summer (Figure 8d), P and AP have a correlation that is similar (-0.53 and -0.55, respectively), indicating that ENSO is also insensitive to Atlantic SSTAs in boreal summer.** Finally, it is notable that although the Walker index and RWS have a strong relationship in boreal spring, the linear fit does not pass through the origin, whereby the P has a strongly negative Walker index but lacks an anomalous RWS. **To further understand the neutral mean response for P , Supplementary Figure S5 shows the RWS field. We find that only the experiments that force the Pacific (P , AP) have a strong negative RWS over the Gulf of Mexico and that this RWS response dominates over the negative RWS over the Caribbean. This RWS may be related to the most southeastern lobe of the PNA pattern, as it strongly overlaps with the Southeastern low presented by Casselman et al. (2021). As a result, even as the Walker cell index may tend towards inducing a positive RWS when forcing the Pacific only, the influence from the Southeastern low may dominate over the influence from the Walker gradient, potentially explaining why the RWS is neutral for P , as opposed to positive.**

The relationship between the different model experiments and Walker index is constant for both boreal spring and summer (Figure 8a,d x-axis), including a positive anomaly for A and a negative anomaly for the P responses. In contrast, the Walker response to AP forcing **varies around 0** for both seasons. However, AP exhibits a large Walker index variance, whereby the anomalies cover much of the range of A and P (see the yellow cross in Figure 8a,d). Thus, this indicates that the Atlantic SSTA can perturb El Niño's influence onto the Walker gradient in boreal spring and summer with an anomaly that is approximately equal and opposite of the Pacific's influence, resulting in a neutral gradient for AP . Overall, **even as the Walker index-RWS correlation is insignificantly different between AP and P , the mean boreal spring Caribbean RWS and Walker cell gradient anomalies for AP and P are significantly different (>95%) (Figure 8a). This indicates that even as the relationship between the Walker index-RWS following an ENSO event is insensitive to Atlantic SSTAs, the individual variables (Walker cell gradient, RWS) are sensitive to changes over the Atlantic. Furthermore, since the mean RWS for P is neutral even with a strongly negative Walker gradient, this overall also indicates that the Walker gradient is not the sole influence on the Caribbean RWS.**

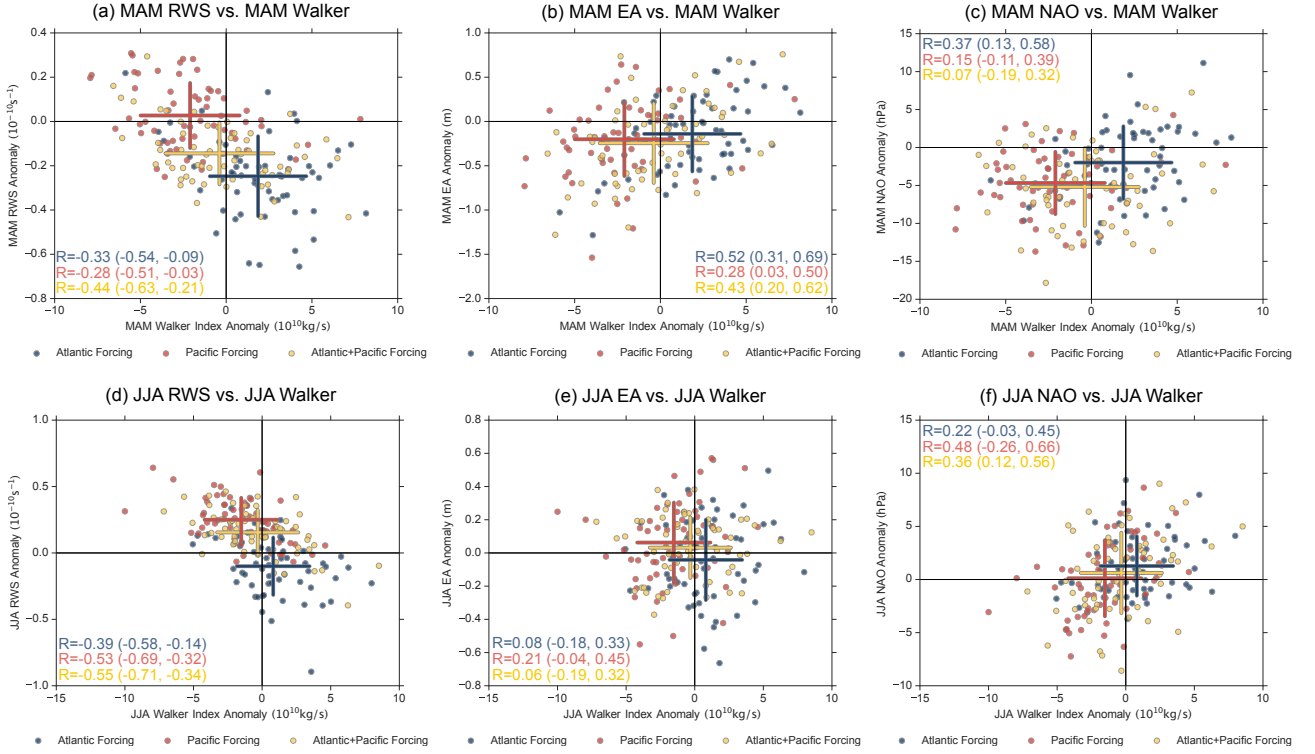


Figure 8. Scatter plot for model data showing the key relationships between the Walker index, RWS index, East Atlantic index, and NAO index. Forcing areas are indicated in the legend, including red, yellow, and blue points for P , AP , and A , respectively. The correlation coefficient (R) is represented in the corner of each panel, with colors representing the forcing area. The central points of the crosses represent the means of all values in each category of the variables indicated both axes. The extent of the crosses indicate one standard deviation in x and y directions.

The relationship between the Walker and EA index also varies considerably between the different experiments, but generally shows a stronger relationship in boreal spring (Figure 8b,e). For boreal spring, the introduction of an Atlantic SSTA (A has an $R = 0.52$) increases the correlation between the Walker index and EA index from 0.28 for P to 0.43 for AP (54% increase). **However, when considering the confidence intervals between AP and P , this correlation difference is not statistically significant.** Furthermore, since the mean EA anomaly for all runs is relatively similar, at around 0 to -0.5 m, this results in little change in the EA anomaly. Conversely, in boreal summer, the correlation is insignificant for both P and AP . Furthermore, forcing both basins together **does not result in a statistically significant change in correlation, and decreases** from 0.21 to 0.06 for P and AP , respectively.

Correlation for boreal spring and summer Walker index and NAO (Figure 8c,f) shows that when the Atlantic SSTA is added (i.e., going from P to AP), the correlation drops. This decrease indicates that the Atlantic SSTA modulates that connection by weakening the Walker cell and NAO relationship. As a result, the correlation is insignificant in boreal spring, while in boreal

summer, we see a statistically significant correlation between the Walker index and NAO. **However, the changes in R between P and AP are not statistically significant.**

To further explain the importance of the Caribbean RWS for influencing the NAE region, we use a partial correlation to
385 remove the influence of the proposed mediating pathway (the Caribbean RWS) from the Walker index-EA/NAO connection
for each experiment (Figure S6). Bivariate correlation shows that the RWS connection to the EA/NAO also changes between P
and AP , whereby the AP shows a notable increase in the NAO connection in boreal spring, resulting in both the RWS-EA/NAO
connections being largest in boreal spring. When removing the RWS influence using a partial correlation in boreal spring for
both P and AP , the Walker index-EA correlation decreases notably, while the Walker index-NAO correlation either increases
390 slightly or has a negligible change (Figure S6, solid vs. dashed red and green lines). Overall, this indicates that the Caribbean
RWS may mediate a potential connection between the Pacific and Atlantic Walker cells and the EA during boreal spring and
the NAO during boreal summer. However, as the partial correlation does not remove all correlation, other external factors may
be at play.

Next, to better understand the NAE regional response, we determine the spatial anomalies in the extratropics by plotting
395 the boreal spring MAM 200 hPa geopotential height response (Figure 9). The A response (Figure 9a) is associated with a
meridional wave train from the tropics to mid-latitudes that curves eastwards in the extratropics. This response is similar to
the EA/ **WR** pattern found by Lim (2015), which was found to be related to Rossby wave propagation from the tropics. Other
studies have also associated this pattern with Atlantic SST variability (Jung et al., 2017; Li et al., 2018; Choi and Ahn, 2019;
Lledó et al., 2020).

400 Forcing the Pacific only (P , Figure 9b) yields a largely negative response over the midlatitudes (around 45°N , 30°W), which
is generally constructive to the A response. Comparing AP and $A+P$ shows that the responses appear to add relatively linearly.
However, when determining the difference between AP and $A+P$ (Figure 9e), we see a statistically significant positive EA
pattern. The EA pattern in Figure 9e indicates that when forcing the two basins simultaneously, the **negative** EA pattern is
weaker during AP than when linearly adding the two basin forcings ($A+P$). As Figure 9e resembles the negative response
405 from A , the nonlinearity seen in 9e is likely due to a weakened Atlantic response. The overall Atlantic response also **creates**
a wave towards the NAE region, but it is altered in comparison to A , as there is a more zonal-like structure in the NAE
region. As a result, there is little overlap of the overall Atlantic contribution with both the EA and NAO modes. This may
explain why we find that El Niño events perturb both the EA and NAO to similar amounts for both P and AP , **and that the**
changes in correlation with the Walker cell gradient were not statistically significant (see Figure 8b-c). **Overall, Atlantic**
410 **SSTAs create a significant difference between AP and P** (stippling in Figure 9f).

For boreal summer (Figure 10) the 200 hPa geopotential height response for A (Figure 10a) lacks a wave train towards the
NAE region. Instead, a strong meridional dipole is present between the Mediterranean and Northern Europe. The lack of a
wave train in boreal summer may be due to changing background conditions. Supplementary Figure S7 shows the background
200 hPa absolute vorticity and zonal winds, which are useful for estimating wave guide locations. Figure S7c-d indicates that
415 the a separation of the subtropical and eddy driven jets changes between boreal spring and summer, whereby a clear separation

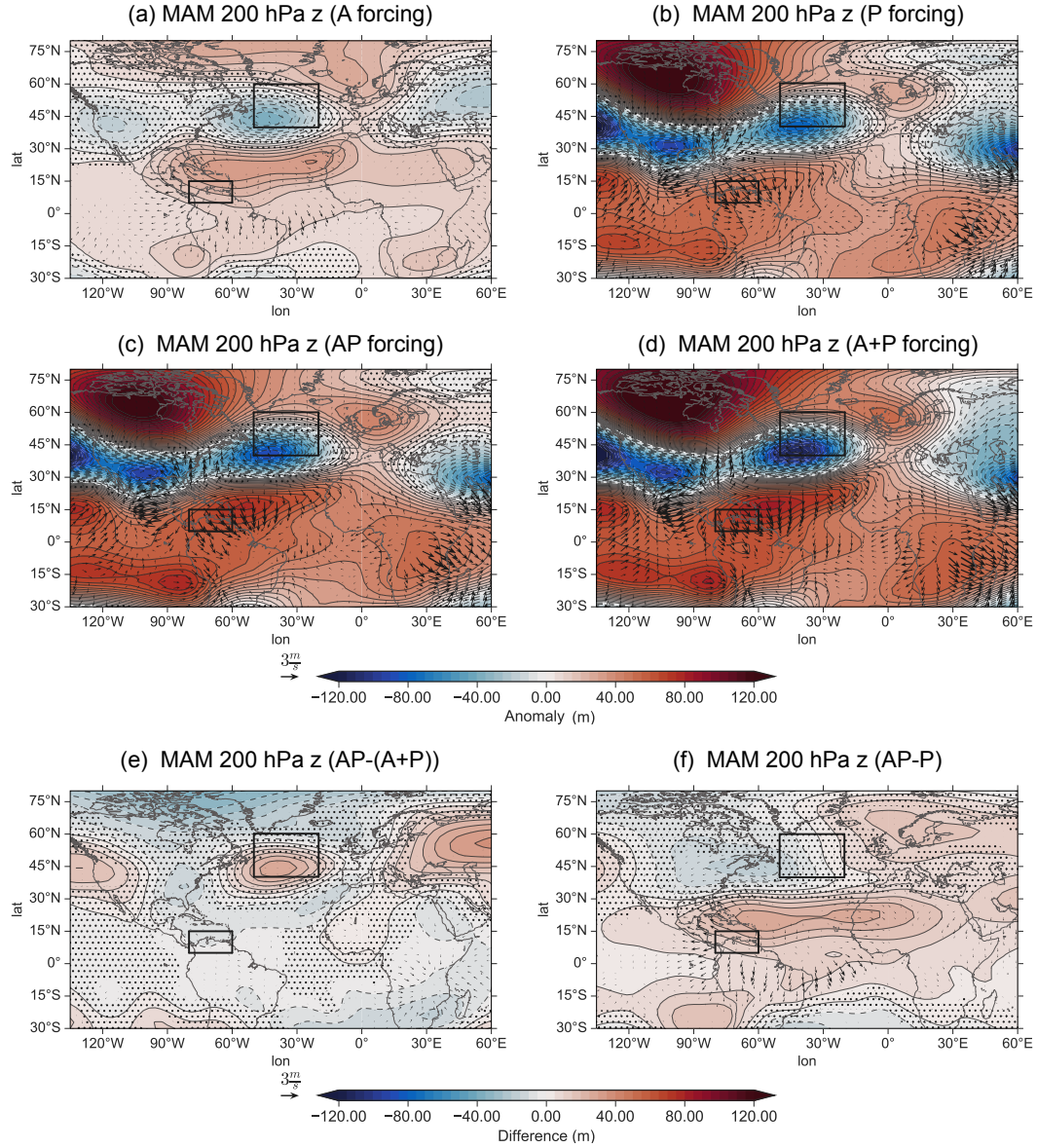


Figure 9. Same as Figure 6, but for MAM 200 hPa geopotential height (shading) and 200 hPa irrotational winds (vectors). Black box in North Atlantic represents the East Atlantic index.

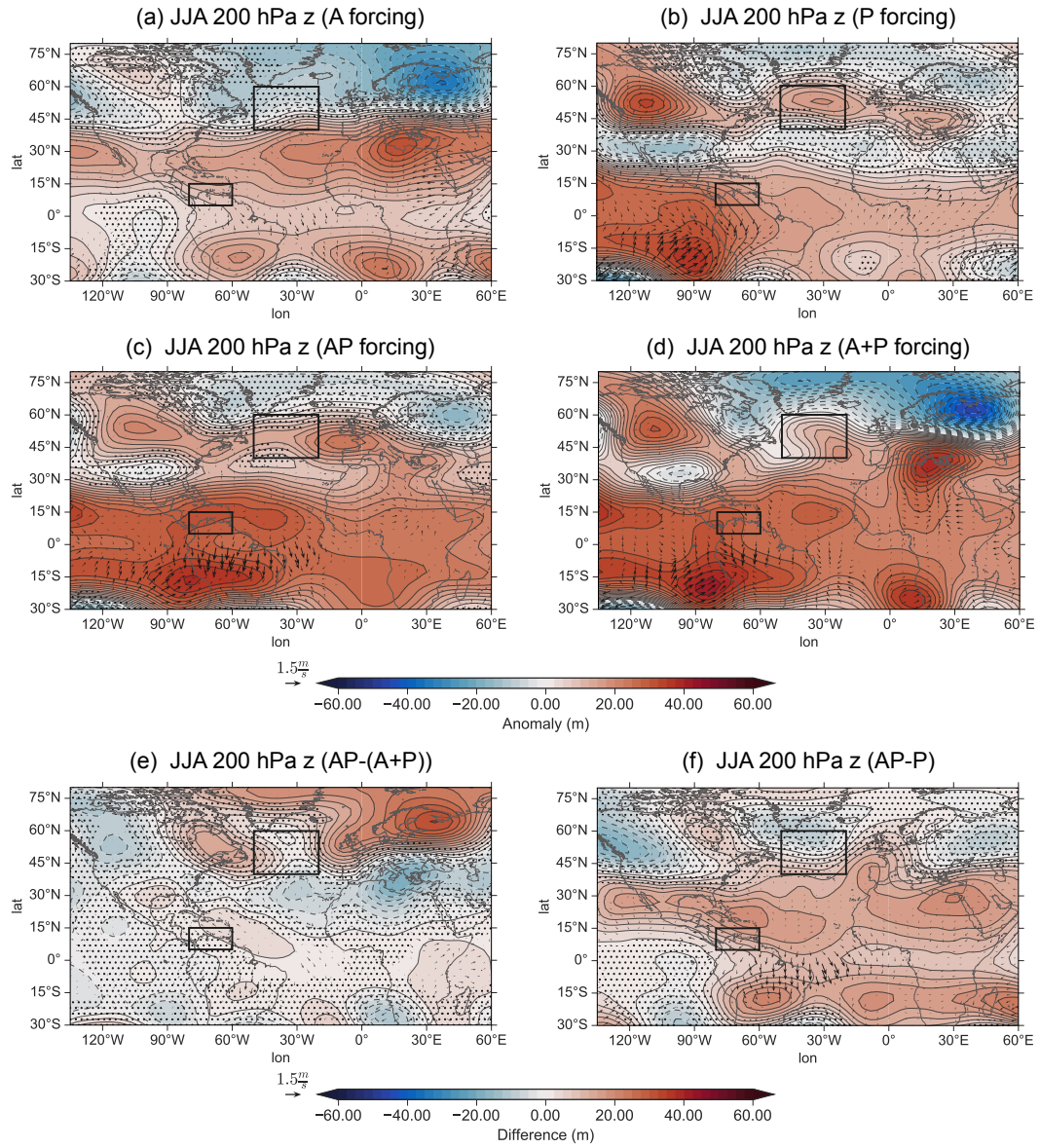


Figure 10. Same as Figure 9, but for JJA.

is only present in boreal spring. As a result, the increased separation of the jets or intensification of the eddy driven jet may create more suitable conditions for the propagation of the wave train from the Caribbean.

For P forcing (Figure 10b), much of the response over the NAE region is insignificant. The exception to this is a significant positive anomaly over the North Atlantic and a dipole over Europe matching the A response in polarity, but with the southern lobe being the only significant area. AP (Figure 10c) shows a response that resembles the P response much more than the A response in the extratropics, indicating that the Pacific response remains the dominant influence in boreal summer over the NAE region, **and that the influence from the Atlantic is small**. This resemblance to P is in contrast to the response for the linear addition ($A+P$), where the dipole shows up more clearly due to the linear combination of A and P .

The difference between AP and $A+P$ (Figure 10e) shows that the NAE anomaly resembles A , but with the opposite sign. Thus the difference between AP and $A+P$ likely occurs due to a **weakened wave propagation in boreal summer compared to boreal spring, or the outcome of the weakened propagation occurring earlier in boreal spring. Here, the residual dipole in boreal summer may be the overall result following boreal spring (see Figure S8 for the evolution of the residual)**. This reduced strength is shown in Figure 10f, where the addition of the Atlantic SSTA forcing results in a weaker response when compared to A alone. Furthermore, the $AP-P$ difference appears to diminish north of the subtropical region, including a significantly reduced negative anomaly over Northern Europe, when compared to A (**Figure S4**). Overall, independently, the Atlantic creates a robust dipole signal in the NAE region (as seen in A), but when added to an El Niño event, this influence is reduced considerably (Figure 10f). Namely, the influence cannot travel as far north, **as seen by the lack of significance in the North Atlantic. Thus**, the Pacific remains the dominant influence on the NAE region into the boreal summer. The Atlantic SSTA primarily modulates an El Niño's response by primarily reinforcing the dipole over Europe, as both lobes are now significant (**Figure 10b vs. Figure 10c**).

4 Discussion and Conclusion

Using MLR analysis and a series of targeted modeling experiments where we force the Pacific and Atlantic basins separately as well as jointly, we find that the tropical North Atlantic modulates the ENSO teleconnection towards the NAE region. To explain the mechanism of this modulation, we first focus on breaking down the tropical interactions, analyzing the Walker cell, and the interactions between the asymmetric and symmetric Gill responses. As far as we are aware, studying the interrelation of Gill responses over the tropical Atlantic is a novel consideration, building on the growing interest in inter-basin interactions and the newly discovered Secondary Gill response by García-Serrano et al. (2017). Furthermore, we hypothesize that the Walker cell interactions between the basins explains the underlying mechanism driving the PCD index (Wulff et al., 2017). The PCD is salient for its ability to **influence** the NAE region via a Rossby wave train, and a potential pathway for the Atlantic to influence the NAE region.

Indeed, by quantifying the Walker circulation using the zonal mass streamfunction over the Pacific and Atlantic regions, we show that the PCD is highly coupled to the Walker cell index. Increasing our physical understanding of how the Atlantic SSTA relates to the PCD index can be instrumental for studies that seek to improve seasonal predictions by using the PCD index,

such as those by Neddermann et al. (2019). Additionally, by using a series of targeted experiments, we show that the Pacific
450 dominates the tropical interaction in boreal spring. The Atlantic contribution is a modulation of the Walker cell, especially
the upper level horizontal winds over South America. When the Secondary Gill response largely subsides by boreal summer,
the Atlantic influences the Walker cell streamfunction more, and also begins to become nonlinear. Thus, our results cast new
light on how hemispherically symmetric and asymmetric Gill responses interact linearly in boreal spring, but nonlinearly in
boreal summer. The source of this nonlinearity may be an intensified Atlantic response in the presence of an El Niño event.
455 This finding can be particularly valuable for studies looking to understand the downstream influence of the tropical Atlantic
on aspects such as rainfall and monsoon patterns, as the strength of the Atlantic Walker cell may change in the presence of a
Pacific forcing (Kucharski et al., 2009; Wang et al., 2009).

When determining the inter-basin interaction on the Walker circulation, using an AGCM may have inherent limitations in
properly resolving the Walker circulation. It could be argued that the horizontal model resolution remains a key limitation. One
460 area where this may be limiting our study is heat balance and the atmosphere's response to SST gradients, which are important
for driving the Walker circulation. Models with higher resolution are better able to balance the response through the transient
atmospheric circulation (Parfitt et al., 2016). Utilizing a moist model with fast condensation that lacks explicit liquid water may
also limit the accurate representation of the Walker circulation in addition to model resolution. This limitation centers around
properly modeling the precipitation and divergence above the tropical Pacific during an El Niño event, which influences Kelvin
465 wave propagation. Downstream, the Kelvin wave can also be influenced by difficulties in representing South American rainfall,
which is a major issue in several AGCMs, as well as many coupled models (Gudgel et al., 2001; Maher et al., 2018; King et al.,
2021). As a result of an altered Kelvin wave, this may limit the accuracy of the Secondary Gill response. Nonetheless, given
that the location of both the Secondary Gill and asymmetric Gill responses match those from reanalysis (Casselman et al.,
2021), we believe that our results are representative of the observations.

470 We also investigate the Caribbean RWS impact on key modes of variability in the NAE region, namely the EA and NAO
patterns. A key finding includes that the Walker index is highly related to the EA pattern in boreal spring and the NAO pattern in
boreal summer. Bringing this further by using a partial correlation to remove the hypothesized mediating pathway (Caribbean
RWS), we show that the RWS may indeed be the mediating pathway. However, when considering the connection between the
Walker cell and Caribbean RWS, the correlation between the Walker index and Caribbean RWS **does not show a statistically**
475 **significant change when** adding the Atlantic SSTA in boreal **spring and** summer. **Thus, when examining the impact for**
Atlantic SSTAs to modulate of the extratropical response through using correlation shifts, we do not see a significant
strengthening of the link between the Walker cell gradient and either EA or NAO in both boreal spring and summer.

By using composite analysis, we show very different extratropical geopotential responses between boreal spring and sum-
mer. A wave train from the tropical Atlantic to the extratropics is only present during boreal spring. The fact that the wave
480 train from the Caribbean to Europe is only present in boreal summer may be due to changing background conditions, **as we see**
separation of the subtropical and eddy driven jets only in boreal spring (Figure S7). To understand how A may mod-
ulate ENSO's connection to the NAE, analysis of the boreal spring wave train following A shows that it overlaps with the
EA pattern. However, as the wave train from the Atlantic changes considerably (i.e., weakens and shifts) for AP, the Atlantic

influence onto the EA changes between *A* and *AP*. **This change between *A* and *AP* may help to explain why the Walker cell connection to the EA is not significantly influenced as the (*AP*-*P*) response in the North Atlantic does not overlap with the EA or NAO areas.**

In boreal summer, the extratropical response to the Atlantic forcing is reduced when forced together with the Pacific (in comparison to *A*), but the tropical Atlantic response is intensified when forced alongside the Pacific. Therefore, it remains unclear what causes the nonlinearity in the extratropical response during boreal summer. **Furthermore**, when considering atmosphere-ocean interactions in the extratropics, there are some key limitations presented when using a series of targeted experiments in an AGCM. The first limitation is that we rely on prescribed SSTs, removing the ability of the ocean to respond to atmospheric processes and also changing thermal damping effects (Barsugli and Battisti, 1998). This simplification is essential in isolating the influence from the tropical Atlantic during an El Niño event but may create issues in the extratropical regions. Here, the NAO is the dominant mode of variability in the NAE region that may act back onto the ocean, in the form of the SST tripole pattern (Peng et al., 2003). However, Baker et al. (2019) found that the tropical Atlantic SSTs are sufficient for properly predicting the NAO response and that the lack of atmosphere-ocean coupling in the North Atlantic does not impact the predictability.

Our results provide a basis for understanding the importance of the TNA SSTA, but they also bring light to several unanswered questions. In this study, by multiplying the forcing by a factor of 4, we assume that the TNA SSTA scale linearly with the strength of ENSO. However, as Casselman et al. (2021) showed, the TNA SSTA may begin to plateau in strength with extreme ENSO events. As a result, one would expect any influences from the TNA SSTA to be reduced during extreme events. This interaction may also increase in importance in the future if climate change influences the strength of ENSO events (Cai et al., 2021). As this study only considers El Niño events, future studies should determine if the negative TNA SSTAs that result from a La Niña interact similarly with the Walker gradient. This may be especially important if the wave activity propagates into the NAE region differently between the positive and negative phases of ENSO (Feng et al., 2017).

Furthermore, the intentional exclusion of ENSO teleconnections **via the** stratosphere through stratospheric nudging likely reduces the sensitivity of the NAO to ENSO. Jiménez-Esteve and Domeisen (2020) found that the interannual variability of the winter NAO variance decreased by 40% when including this nudging, which may result in misrepresenting the importance of the TNA for influencing the NAE region. However, as the stratospheric pathway is likely weaker in MAM and JJA as compared to mid-winter or early spring, we do not expect that removing the stratospheric influence in our study should change the NAE response in a major way. Nonetheless, future studies should determine the importance of the TNA SSTA for modulating the full influence from ENSO through all pathways.

Code and data availability. To access the JRA-55 and ERSSTv4 datasets, they are available at the NCAR data archive (<https://rda.ucar.edu/>). The Isca modeling framework was accessed from the GitHub repository (<https://github.com/ExeClim/Isca>, last access: May 2020) (Vallis et al., 2018).

Author contributions. JWC performed the model simulations, analysis, and writing of the manuscript. BJE contributed to the setup of the AGCM and to editing the manuscript. DIVD contributed to analysis and interpretation of the results as well as writing the manuscript.

Competing interests. The authors declare that they have no conflict of interest

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