Point by Point Response & Changes to Manuscript

R – Referee comment ; **A** – Author response ; **C** – Manuscript change

Referee #1:

Major Comments:

R: the authors put a lot of emphasis in the conclusion on the necessity to better understand the connection between mean flow and associated teleconnection patterns. But in their results the authors mainly discuss wave patterns. Maybe it could be helpful to put some more focus into the mean flow for the discussion of their results. E.g. the authors successfully did overlay the MMM V trend and the regional EOFs, but Fig. 11 only shows one contour of the mean flow (20m/s). Therefore the reader is not able to interpret the anomalies, because there is no relation to the spatial variance of the mean flow. Further the authors could focus a little bit more on the role of the mean flow in their discussion. This could maybe also include some large scale global flow anomalies associated with NAO, PNA, ENSO, etc. The anomalous patterns in the jet strength in their Fig. 11 seem to show similarity to such known global pattern indices. Further, there are already some studies looking at the connection between large scale flow patterns and the resulting wave response (or how they are associated, not suggesting a cause-effect relationship). I think this was also done in the reference they cite (Souders et al, 2014), so maybe could be worth including in their discussion (how do their findings of wave packet anomalies relate to the finding here)?
A: We added a more detailed plot showing the jet bias, while highlighting the importance of it being found in the Historical model bias (meaning that this is not an artefact of the transient CTP pattern itself). We also added an explanation into a possible link between the CTP and NAO. Using Wolf et al (2018) and Watanabe (2004), we found that in the ensemble, the AS pattern is much more likely to occur during the positive NAO phase. This means that future NAO trends (specifically, a positive shift) might force more specific CTP phases. This is now detailed throughout the article, and shown in Figure 12. As for the PNA, unlike the NAO, we find it hard to separate this mode from the synoptic scale NA RWPs, as they share roughly the same domain.
C: Background - Specifically, the NAO can act as a precursor to such RWPs, affecting their path and amplitude (Watanabe, 2004; Wolf et al., 2018).

Methods - To test the NAO's possible role in forcing the CTP, we use a standard NAO index (Hurrell et al, 2003): projection of monthly sea-level pressure (SLP) anomalies onto the leading EOF of the seasonal SLP anomaly in the North Atlantic sector (20° N-70° N; 90° W-40° E). Positive and negative NAO phases are defined as months when the index exceeds one standard deviation (+-sigma).

Results - As for other large scale modes which can trigger the CTP, the phase of the NAO was found to be correlated with the occurrence of monthly CTP preferred patterns in the AS region. For seven models of the AS group, we calculated the share of preferably phased Future CTP months to happen concurrently with a positive or negative NAO phase. For six of the seven models, the monthly AS CTP pattern is at least twice as likely to occur with a positive NAO phase (Fig. 12). No such relation was found for preferred NA phases (not shown).

Discussion - Large scale internal modes also act as forcing for the CTP. The monthly AS pattern, specifically, was found to be correlated with phasesof the NAO, being twice as likely to occur during the positive NAO phase compared to the negative one. This connection is in agreement with previous studies dealing with quasi-stationary wavepackets and the NAO. Wolf et al (2018) found a strong correlation between negative seasonal NAO values and decreased wave activity in the midlatitudes. Additionally, RWPs reminiscent of the preferred AS pattern can be found in Watanabe (2004), where they are identified as an Asian extension lagging positive NAO events. It is therefore possible that, within the AS group, some common trend for NAO variability (like a general shift towards its positive phase) forces this regional CTP pattern. This hypothesis is beyond the scope of this study.

R: Authors are analysing wave pattern with non-zonal waveguide. Wouldn't it then not make more sense to use the wind perpendicular to the climatology (as representation of the waveguide)? Wolf and Wirth (2017, Diagnosing the horizontal Propagation of Rossby Wave Packets along the Midlatitude Waveguide) have shown that this does have an important impact on identifying the correct path of propagating waves. Here the authors do focus on stationary or quasi-stationary waves, but as soon as the waveguide has a meridional component, the more physical quantity to measure the wave is the wind perpendicular to its waveguide. What is the authors point on this, do they assume they would see an even clearer signal in their results or do they expect that this does not have a relevant impact on their results because of the large scale of the wave patterns they are investigating?
A: Our work mostly relies on EOF analysis, which unlike RWP tracking, is not limited to the horizontal propagation of the waves. The meandering shape of the zonal waves in the EOFs shows that they capture the climatology of the waveguide. However, this is not to say that the method shown in Wolf & Wirth (2017) won't be useful. In the daily calculations, using perpendicular flow might help us obtain a slightly cleaner picture (better RWP accounting), but we don't expect it to meaningfully alter our conclusion.

Minor Comments:

R: p.1, line 21: Why do the authors only highlight "shifts" in the climatological mean flow? The strength of the mean flow is important as well, isn't it?

A: Changed "shifts" to "changes" to avoid confusion.

R: p.2, line 37-40: Could the authors please give some more explanation on this for the reader who is not familar with the details of Branstator 2002? As this point is crucial for the paper, it seems that some more explanation on this is well invested. How crucial is the exact way of calculating the EOFs and how should they be calculated? I assume they are calculated for the whole hemisphere, either northern or southern hemisphere. The EOFs are further calculated for DJF using subseasonal anomalies - does this mean the deviation of the meridional wind from the mean of the specific season or the deviation from all seasons taken together? As there is still a shift of the jet during the season, would using the meridional wind as deviation from a running mean or low pass filtered signal change the resulting EOF signals or are they a very robust signal? Further, the first two EOFs do show a very similar but shifted wavenumber 5 pattern with more or less opposite sign? Otherwise this combination given in Equ. (1) would make no sense as it tries to capture the phase of a wave that can have nonzero phase propagation, right? How many variance is explained by these EOFs and are they well separated from the next order EOFs? -> I think this was explained later in more detail, so maybe refering to this here or including a short descriptions to make the reader more familiar with what this method does capture/what the associated pattern represent.

A: Provided further explanation on Branstator's original method while also highlighting the robustness of the patterns. Additionally, we now mention that EOF details are provided later in the paper.

C: One method commonly used for isolating these patterns is Empirical Orthogonal Functions (EOF) analysis. In B02, the author calculated the two leading EOFs of the subseasonal anomalies of monthly 300 hPa meridional wind for the entire NH. This means that each season's mean was removed from every monthly mean V map. The resulting patterns, a pair of rather similar number-5 waves in quadrature, were found to be very robust. B02 showed that they can be produced from different fields' EOFs, as well as other methods altogether (like one-point correlation). Further explanations on the EOFs used in this study are provided in Sections 2 and 3.1.

R: p.2, lines 48-50 Maybe this description of RWPs must be reformulated? RWPs are not necessarily restricted to 1 or 2 wavelengths. Further they are not necessarily consisting of pairs of troughs and ridges; if one has identified a RWP consisting of a trough and a ridge which further leads to downstream development than there will appear either a trough or a ridge, but not necessarily a pair of both (or by decay of individual anomalieson upstream side).

A: Changed the wording so it's clear we're talking about RWPs that are associated with the CTP specifically. Also, removed the mention of trough-ridge "pairs".

C: These RWPs, sometimes called wave trains, are local synoptic structures. The ones that are associated with the CTP are typically comprised of one or two wavelengths, seen as a sequence of troughs and ridges in geopotential height, or as alternating northward-southward anomalies in meridional wind. One noteworthy feature of these specific RWPs is their velocity. They have positive zonal group velocity and near-zero phase velocity …

R: How do the authors conclude what the value of the phase speed (nearzero) of the RWPs is that contribute to the CTP?

A: This is a common interpretation of the CTP (see references in lines 69-70) – a subseasonal signal which is actually composed of persistent quasi-stationary patterns in the synoptic scale. If the waves had a non-zero phase speed, they would not appear so clearly on subseasonal data.

C: This makes the CTP a unique bridge between timescales. The prevalence and quasi-stationary nature of these specific synoptic RWPs allow their influence to manifest on a subseasonal scale as well. …

R: p.3, lines 63-64: What is the statmenet here? The CTP is already a current wintertime feature, so what do the authors mean by "CTP will be easily excitable by future greenhouse gas forcing"? The statement is that the CTP pattern will become stronger? Also following lines, the authors mention the "CTP-like trend". This means a strengthening of the current CTP pattern or what does the term "CTP-like" mean here? A CTP-like trend could also be a weakening of this pattern or not?

A: We changed the phrasing so it's clearer that the CTP isn't a future-climate pattern, but rather, its presence is clearly seen in the projected long-term trend.

C: It has been previously posited that the CTP, as a low frequency internal mode, will be excited more frequently in the future, as greenhouse gas (GHG) forcing grows stronger.

R: paragraph lines 67-73: this paragraph describes to what the authors previously refered as linear RW theory (p.2, line 35), correct? The increase of jet strength in winter does lead to a shift in zonal wavenumber toward smaller values. What do the authors mean here when they say that this is not necessarily the case in boreal summer? The strength of the jet in boreal summer does not have an impact on the stationary wavenumbers? r is the focus here on the excitation/amplification of wave responses than rather a shift of wavenumbers (what exactly are the authors refering to by using "the response")?
A: The wintertime CTP trend is mainly explained through linear theory, yes. We expanded a bit on the topic of the boreal summer CTP response, where soil moisture and convective heating play an important role in teleconnection amplification. On that note, "teleconnection amplification" can mean either wavenumber shift or wave amplification, as lo(convective heating, land interactions)ng as the result is a stronger signature of the teleconnection on longer timescales.

C: For the summertime waveguide, the driving mechanism might be more complex, as signs show that changes in the diabatic forcing (convective heating, land interactions) play an important role in the amplification of the teleconnection Ten & Branstator, 2019).

R: p.3, lines 77-78: why is it surprising that seasonal and subseasonal variance of V behave differently? If there is a shift in the power spectra of meridional wind towards lower wavenumbers this could probably also mean a shift towards lower phase speeds (?). If there is an increase in more quasi-stationary wave patterns the contribution of the faster propagating signal could decrease (what one would probably expect if one sees more stationary wave patterns or do I confuse sth here?).
A: We find the Wills et al results surprising because they are specifically analyzing QSW variance on a subseasonal scale (we put more emphasis on this in this version). This means that it's not a decrease in the contribution of fast propagating waves, but rather stationary components. We address this discrepancy further in the Conclusions section.
C: on the subseasonal scale, the variance of quasi-stationary waves (calculated using 300 hPa zonal V anomalies) is surprisingly projected to decrease, in an apparent contrast to the seasonal signature

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R: p.4, lines 99-100: Doesn't this subtraction of the seasonal mean automatically cause some anomalies by the shift of the jet position. What would happen if one would remove something like a running mean of 90 days, would this have a huge impact on the result? -> I think I mentioned this further above already in a bit more detail.
A: We recalculated the EOFs using 90 day means for reanalysis and CMIP5, and it does not seem to change our results. For a few models, the patterns in the EOFs are clearer over the AS sector, but for reanalysis and for most of the ensemble there is no major difference between the resulting patterns. When the original EOF is projected onto the running-mean EOF, the majority of models score 0.85 or higher.

R: No colorbar in Fig 1
A: Added a colorbar

R: p.5, paragraph lines 139-148: Again, the climatological background field is evolving over the period of the winter. What is the reasoning to subtract the full DJF mean instead of the climatology for the individual months. Wouldn't that be more physical with the reasoning given in this paragraph (to get rid of the evolving planetary scale for the anomalies)? Did the author estimate the impact of using monthly climatologies instead of seasonal climatologies?
A: We performed the calculations again with monthly climatology and it did not affect our results. Specifically, changes in the mean projection index (used to determine the model subgroup and preferred phase) were in the order of 10^{-3}.

R: p.5, line 148: why are the data with low projection scores excluded and how were these 70% chosen. Do results depend on the percentage?
A: Weakly projected months will form an angle on the phase space, but this value doesn't have any physical meaning
C: We average all highly projected monthly index values to obtain the mean projection score of every experimental run. This is done after excluding data with low projections scores (below the 70th percentile of index magnitude), as these months' phase index doesn't have physical meaning. Our results are not sensitive to the choice of percentile.

R: p.5, lines 149-50: Could the authors explain why the focus should be on models with a specific phasing, which do represent a higher score? What would happen if specific models would produce a persistent pattern of an overall slowly evolving pattern. Let's say often a very strong Ridge over the Rockies with downstream amplified wave pattern, as given by EOF1 in Fig.2. If this pattern would break down towards the mid/end of the season with a more zonal flow, this more zonal flow would appear as opposite sign of the EOF1 (ridge less strong than for climatology, downstream meridional tilt of the jet less strong), wouldn't it? This process would represent the recurrent build up and destruction of a specific wave pattern. If such a case would happen it would not be identified in the

average score (it would average to zero), right? Could the author comment on this, why they think something like this is not expected to occur or if it would occur, why it would be fine if the score would still identify it as close to origin (not specific relevant wave pattern case)? Or differently formulated, why is the strong focus exclusively on a prefered phase?
A: Our method only captured wavy months. For a near-zero mean index, a model should have wavy months with different longitudinal phases (for instance positive/negative EOF1 patterns). In the scenario described in the comment, the destruction of the wave pattern (zonal flow) will have a low projection score (below 70th percentile) and therefore will be filtered out.

R: p.6, line 157 (CTP events): So, usually if the authors talk about CTP they have in mind the patterns derived from the EOF of monthly fields. How does such a CTP relate to the CTP events mentioned here in this paragraph. Do the CTP events using daily data (with a high index) mainly represent two RWPs which are located in a way that they have at the same time the correct phasing relative to the "monthly" CTP pattern? Or are those events only restricted to specific regions (the 144 lon mentioned earlier) not for the whole hemisphere. An eastward propagating (phase propagation) RWP will then be captured several times moving through this region (after moving one wavelength). This means, if I understand it correctly, two RWPs at lag 0 in the composite, could actually be the same RWP at lag 0 and then something like 5 days later after shifting a whole wavelength further eastward if it consists of more than one wavelength (because in the time in between it will not fullfill the phase criteria given in line 161). Is that correct? What would this mean for interpreting these lag-composites?
A: CTP events were defined in order to examine the preferably-phased monthly pattern on a finer temporal resolution. They have the same specific regions and phases. By definition, their projection index (and phase) is persistent for a few days, so we capture only QSWs. That is why waves with phase propagation will not be captured. We changed the wording in the paragraph to clarify these points.
C: We define "CTP events" in daily mean data, which are essentially a synoptic manifestation of the wave patterns that are found in monthly data. We capture quasi-stationary Rossby wave packets that are in the same domain and nearly in phase with the preferably phased monthly patterns (only on the 500 hPa level, as explained previously).

R: p.6, line 161: This phi_d and phi_m refer to the phase as used for the phase in Equ. (1) which was given by gamma, right? So to be clearer and reduce confusion, it could help to be consistent and name them the same way (gamma_d and gamma_m).
A: True. Changed to gamma.

R: p.6, line 163: What is the future climatology? is this a similar 30 year average (which period?) as for the historical climatology (1900-1930)?
A: 2070-2099, the same period used for the trend (Future minus Past). Added the years to this paragraph

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R: p.6, lines 175-178: How do the percentages compare to the findings of B02, weren’t they significantly higher and if so, how can the differences be explained. For the separation of the EOFs it does not really matter if the first two are clearly separated, if they are both used or combined in the index of Equ. (1). However, doesn’t the close connection to the third EOF mean that it is difficult to analyse them seperately? How does this change for a longer dataset (NCEP-I), are they well seperated from each other or to the third EOF? What is the consequence for this (as the authors mention specifically this test)?
A: In B02, the global vEOFs explain 22% & 13%, but they are calculated for CCSM3 which tends to overshoot compared to reanalysis. In our analysis, for instance, CCSM4 gets 16% and 13% compared to NCEP’s 13.6% and 10.8%. As for the separation, according to North et al, when two functions are not separated it means that their individual patterns are actually a random mixture of the two true eigenvectors. This muddles the physical interpretation of our 2D index, so we tried to avoid it by using NCEP (where the first two functions are separated from the third).

R: p.6, line 185 (Fig.S1 - Fig.3): the multimodel mean has higher absolute values than the individual models. It seems like the Fig. S1 only show the first two contours, ommitting the following ones.
A: The third contour and onward were omitted for clarity (Fig S1 is very dense). We now specify this in the caption.

R: p.7, line 195: I have some difficulty to interpret those number of 0.78 and 0.5 – what is the score range? 1 is as mentioned a perfect copy. What is the lowest score, 0 or -1? And the lowest score is then the exact opposite of the signal? If that is the case and looking at Fig. S1, this suggests -1 is the lowest skill score, otherwise 0.5 would somehow be like a wavenumber 5 signal with random phasing compared to observations (which obviously is not the case according to Fig. 3). Probably it would be helpful if the authors could give the reader some idea what this score does tell (apart from the upper boundary).
A: Added an explanation fo**r** the scale of the index.
C: Zonal number 5 patterns will have a large absolute score (1 for a perfect copy, -1 for the same wave in antiphase), and a zero score represents some very dissimilar pattern.

R: p.7, line 1999-200: The quasi-stationary wavenumber 5 pattern is per se not a response of GHG forcing as it is already present in the historical data. Is this comment about the trend and differences of this pattern to the historical pattern? Maybe the authors could clarify this.
A: We are referring to the trend (future minus past) which looks like a zonal QSW. We elaborate further in the following paragraph. Changed the word "response" to "trend" in order to avoid confusion
C: A quasi-stationary zonal number 5 wave in the northern hemisphere appears to be a prominent feature of the projected circulation trend in high emission scenarios.

R: p.7, line 204 (Fig. 4): (1) It could be helpful for the reader if the authors would include here the underlying past climatology. (2) Does the MMM response really shows a convincing wavenumber 5 signal? There seems to be a low wavenumber signal over eastern asia/western pacific and a higher wavenumber response over North America/Atlantic. A Fourier analysis would probably not show a single peak at wavenumber 5. (3) The authors further say that although this wavenumber 5 response shows up in the MMM (Fig. 4a), the individual models trends represent only low scores if projected onto the EOFs. This seems to suggest that the MMM response has a high score, but is this really the case? Looking at the response wave signal path from North America southward into the Atantic, this does not seem to have a counterpart in the EOFs from Fig. 2. Does the MMM shows a much higher score? (4) Further, I like that the authors included the supplementary Fig. S1 showing all models. But I would have been even more interested in the same kind of Figure, but based on future data as there is a very good agreement between the historical EOFs between models and observations, but there seems to be some stronger discrepancies in the wave response for future projections. So it is not really obvious that the future projections go for a CTP pattern or rather increase in the evolution of separated wave responses as can be seen to some extent already in Fig. S1 for some models in the historical data (EOF2 showing a seperate NA wave pattern?).
A: (1) Added the MMM climatology to Fig. 4
(2) It is true that locally, some parts of the wave are not pure wavenumber 5. But we feel confident to the overall global pattern as a number 5 wave. This is also represented in the Fourier analysis of this exact trend in Simpson et al (2016).
(3) The difference the explained variance between global and regional EOFs is perhaps phrased confusingly. It's not that the trend is similar to the MMM EOFs, but not for individual models. Rather, that using global EOFs is too limiting in terms of capturing the phase of the trend (which is different for different regions). When we split the global EOFs, we get two sets of smaller (but similar looking) EOFs, and the combination of all four allows us to describe the trend. We changed the order of the paragraphs describing this and also added additional explanation (see below).
(4) Added each models EOFs based of RCP8.5 data to supplementary material (Fig. S2)
C: (3) This allows us to use only these regional functions for our analysis (two EOFs for each region). This improvement might seem surprising, considering the spatial similarity between the global and

regional EOFs (see Fig. S2 in the supplementary material). However, this is by virtue of the added degrees of freedom (an index consisting of four regional projections, instead of two global ones).

R: p.7, line 207: what exactly is the point that should be tested further? Is it the low projection score?
A: This is related to the previous point (3). We want to show that regional EOFs are better for describing the trend.
C: In order to confirm that the regional EOFs are more suited for describing the trend, we calculated…

R: p.7, lines 213-214: Why does the division into different regions allow to inspect CTPlike responses? Could it not be that doing the calculations for different non-global regions highlights regional wave patterns that are not circumglobal? Fig. 4b shows that the variance of most models cannot be explained captured by the MMM global EOFs, but mainly by EOF 4 (is that correct interpretation?). Wouldn't it be interesting to show this EOF 4? Is it a non global wave pattern of a higher wavenumber? If so, wouldn't that mean that for the future trend the CTP pattern is less relevant and the projections tend to prefer another global wave response? Why isn't that the interpretation of Fig. 4aa and b.
A: We hope that this issue is now better explained by our previous changes of pg. 7. We interpret the results in Fig 4 as added degrees of freedom in the phase index. This is strengthened by what we see in daily data – RWPs that correspond to regional EOFs propagate much further (in the AS, nearly circumglobally).
As for the global EOF4, we find it less relevant for 2 reasons: while it helps with visualization, the MMM EOF (constructed as a composite of 36 different EOFs) lacks clear physical meaning. This is because every model has different internal variability. Secondly, the variance of the dataset (lambda) explained by EOF4 is much lower, by design, than that of EOF1&2.

R: p.7, line 217 (Fig. S2): What are the values for shading and contours? Shouldn't be the shading in Fig. S2 be identical to the contours in Fig. 3? But blue values increase in Fig. S2 while at the same time red values decrease in spatial extent. Does this mean that the colour contouring is asymmetric between negative nad positive values in Fig. S2?
A: Fixed so that the shading in Fig 3 and S2 is the same.

R: p.7, lines 217-219: This is not shown anywhere or is it? The reader hasn't seen the regional EOFs for the obersvational data. So maybe indicating this by sth like "(not shown)".
A: Added "(not shown)" to this sentence.

R: - p.7/8, lines 220-224: Any conclusion or interpretation the authors could provide the readers? Comparing the regional to the global EOFs in Fig. S2 I'm surprised thismakes so much of a difference. But the wave pattern for the EOF1 in NA (Fig. S2a) seems to show a wave pattern coming from the south and pointing to the south, suggesting that this wave pattern does not feature a CTP pattern. Could the authors provide some explanation and interpretation to their results. It seems here that the authors now just use the regional EOFs because they better represent the trend of the models. But why is that, is there some possible explanations behind these signals or is this just a useful thing to do to capture the trend, because going to smaller scales usually should allow one at some scale to capture all globaltrends if added together.
A: We addressed this point for previous comments. Hopefully our interpretation (more degrees of freedom in an index including four phases) now comes across in the revised version.

R: p.8, lines 234-235: (1) I really like the visualization of the data in this phase space diagram of Fig. 5. However, what is the measure of uniformly spread? Starting to look at Fig. 5a this seems a bit strange, as the negative phase of EOF2 does not seem to occur very often for weak EOF1 values, in one of the eight parts there are only 4 blue dots, whereas in others there are more then 20. So it is not really uniformly. Could the authors quantify this to some extent with sth like X % in a 90 degree angle range? That shouldn't be too difficult and this would allow them to make their point more convincingly of how much more the RCP8.5 data is concentrated into a specific region of

the phase space diagram. Probably not necessary, as now I realize this is what Fig. 6 does. (2) Further to this, Fig. 5 does only show one model, right? This should be mentioned by the authors (it is described as all models in the text), so I totally missed this at the beginning.
A: (1) We agree that Fig 6 gets across the point of uniformity. (2) We changed the phrasing to emphasize it being single models.
C: For all 36 models, historical data is spread approximately uniformly on the phase space (blue dots in Fig. 5, shown for two single model examples)

R: - p.8, line 238: Is it obvious that models shows a preference for either NA or AS regions. Is it necessarily "either" for being able to explain why they not project strongly onthe global pattern? Isn't it possible that one model prefer boths, some periods with increased wave patterns over the AS which ressemble the given EOFs there, and some periods with increased wave patterns in the NA region with some arbitrary signal everywhere else. The authors seem to exclude this possibility. What is the reasoning for their conclusion?
A: We mention this in the following paragraph: " … Eight models display a preference in the AS region, with negative (positive) scores for the regional EOF1 (EOF2). Two additional models show these tendencies for both domains". We changed the previous line saying "either" domains to reflect this.
C: most models show a preference for certain phases, for either the NA or AS regions (or both, in the case of two specific models).

R: p.8, line 244 (Fig. 6): How is the circle calculated? Not clear to me where the assymetry of the circle (right vs left and top vs bottom of the phase space) comes from. This is the standard deviation in physcial space of the individual model monthly data also projected onto the EOFs and then shown in this phase space? If it is the standard deviation of the values in this phase space (as it does sound like in the text), shouldn't it have an equal distant from the origin - or does the circle only seems asymmetrical because of the dashed lines which do not represent an adequate measure of distance?
A: It is indeed the STD of the values shown in the phase space. The asymmetry is a graphical issue. We fixed this in this version.
C: Fixed the circle shape in the plots and the order of Fig 6 subplots

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R: p.8, lines 246-247: I'm still confused with everything related to this sigma-measure. Aren't most of the rectangles of RCP8.5 inside the circle? The filled ones represent the same models (the group) in Fig. 6a and 6b, right? But this would mean that most models don't get above 1 sigma for any region or do I misunderstand the plots? Further, isn't the standard deviation calculated from the RCP8.5, so wouldn't we expect most models to be inside of the circle by definition (for simplicity assuming a normal distribution)?
A: Your interpretation is correct. Most models do stay inside each circle separately (as can be seen in Fig 6). But when you add up all models from both regions, you get 19 out of 36 models outside (9 in NA, 8 in AS and 2 in both). The wording was a bit misleading, so we changed "most" to "more than half".
C: In contrast, more than half of the ensemble's RCP8.5 runs have a mean projection score bigger than 1 sigma for at least one region

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R: p.8, lines 247-249: Maybe the authors could spend some more time better explain this. I was expecting them to refer to the red rectangles (the mean projection of the RCP8.5 models), but I cannot identify those numbers? First of all, I assume the authors refer to rectangles outside of the circle, but they mention only the sign of the EOF (which would include all of the red rectangles). Further I can identify the eight rectangles outside of the circle in the NA region but not for the AS region (is that because they are on top of each other?).
p.8, line 251: Again, do the authors really mean non-zero or outside of the circle, because their statement is only true for those outside of the circle, isn't it? Following line as well, this is about the rectangles outside of the circle. The 7 cases are then the 6 inside the quadrant and the one with nearly 0 EOF1 very close to it, right? But how can these numbers be associated with the previous

statement of 8 cases with negative (positive) EOF1 (EOF2) for the AS, (representing the second quadrant)?

A: We are indeed referring to the models that are outside of the circle. Some were overlapping so it was hard to tell. We changed the shape to circles with a white outline so that they will be clearer.

C: Interestingly, we can identify a common phasing that is shared by all strongly projecting models in each region (in Fig. 6, these are the filled red rectangles which are outside the circle)

R: p.10, line 288: How is it filtered? Difficult to follow in detail, if it is just mentioned that the data is filtered without specifying how.

A: Added details about the filtering in the supplementary file.

C: … Two consecutive sequences that are not separated by at least 48 hours are considered one CTP event. Our results were not found to be sensitive to the choice of these parameters. This method of filtering results in some false positive matches. We therefore further filter out all sequences whose composite does not display a wavy signature (alternating mean negative-positive-negative anomalies in the boxes marked in Fig. 8c).

R: p.10, lines 290-293: Can the authors say anything about the persistence of the CTP events? p.10, lines 305-309: The authors are measuring also the persistence of the the signal (as this is part of the definition of a CTP event). Would be nice if they could make a statement about the persistence of those events. This should also be sth of interest in terms of climate extreme, because such persistent signal do often lead to extreme events. So knowing about the trend in the persistence could give some hints about the evolution of possible extremes.

A: Added information about the average length of CTP events.

C: The average lifetime of the wavepackets does not change between the runs, and was found to be 6 and 5.5 days for IPSL and MIROC, respectively.

R: p.10, lines 296-297: Is this really the case? The regions are very different with a shift of partly 60 degrees and huge overlaps. The NA region here captures main parts of both, the Pacific and Atlantic region in Souders et al. (2014). But I assume it depends for what this comparison is used and there is no need for a good agreement between the chosen regions. The authors directly refer to Souder's result of RWP formation, in which case most of the RWP formed in the Pacific region will result in amplified RWPs over the NA region given here, whereas the formation of RWPs in Souder's Atlantic region will contribute to the RWP in the AS region given here - although a direct comparison is not simple because Pacific RWPs could also go all the way towards the AS region whereas RWPs formed in the Atlantic can also decay in the Atlantic.

A: That's true. The comparison is not straightforward, so we decided to remove the region comparison and add the comment on one RWP contributing to both groups.

C: Note that the comparison to our results is not straightforward. For instance, a RWP formed in the Pacific might be categorized in both of our groups (depending on its path). Additionally, our CTP events likely constitute only a small subset …

R: p.10, lines 297-298: Difficult to compare as Souder's climatology also captures faster propagating RWPs with wavenumbers around 10. So I agree with the authors that Souder's climatology should give a high upper boundary. The waves the authors are interested in (low wavenumbers around 5) should be more comparable with the quasistationary waves investigated in Wolf et al. (2018, Quasi-stationary waves and their impact on European weather and extreme events). Their Fig. 9 should probably give a lower boundary for the wave occurrences with about 0.6 per season in ERA Interim for very persistent wave signals (minimum 10 day lifetime). So the findings here seem to be well in this range of different climatologies.

A: Thank you for bringing this interesting paper to our attention. We now mention this climatology as well in this paragraph.

C: Another more specific bound can be found in a work by Wolf et al. (2018). The authors examined the climatology of long-lived quasi-stationary waves using the ERA-Interim dataset, and found an average of ~0.6 instances per winter (DJF) of waves with a lifetime of 10 days or more. This is more directly related to circumglobal RWPs, which typically require more than a week to complete their path.

R: p.10, line 306: Maybe not using the term "wave activity", which would be strictly speaking a measure of wave strength/amplitude, but here the authors rather mean frequency.
A: Changed “wave activity” to “wave frequency”

R: p.10, lines 312-313: Why is the RWP at its peak of the life cycle at lag 0? Strictly speaking, one cannot tell this with the applied measure which can only tell its projection peak onto the CTP. But even this probably does not occur at lag 0, or does it? Lag zero is defined as the first of at least 3 consecutive days when the projection value excees the given threshold. But then, would it not be more likely that the peak occurs around day 1 or slightly afterwards?
A: Removed the mention of “peak” and instead, refer to the waves as “somewhat developed”.
C: By definition, each such lag 0 day has a high projection score on the preferred phase, meaning that the RWP is already past its initial excitation and is at least somewhat developed.

R: p.10, lines 315-316: where does this conclusion come from? What characteristics specifically and how where they affirmed to be realistic? Where does the conlusion for near stationarity comes from? Not clear where the conclusion and description of RWP comes from in this paragraph. Could the author give some more details and explanations for this paragraph?
A: These claims are based on the analysis of the composite RWPs. We changed the phrasing to emphasize this and to refer the reader to Figure 10. Also, added an explanation for the stationarity of the waves.
C: These composite wave packets (seen in Fig. 10) display realistic characteristics that have been previously affirmed in reanalysis and models … : Their centers of action remain fairly stationary throughout, meaning that they indeed have near-zero phase speed. This is by construction, as the RWPs were chosen to have persistent strong projections onto the same phase.

R: p.11, lines 320-325: How do the author conclude that the wave source is located over Southeast Asia (IPSL case) when there is no statistical significant signal over southeast asia and no clear wave propagation. Further lag 2 and 5 seem to indicate eastward moving phases, contradicting the assumption of a stationary or near stationary signal. This raises again he question if there are not also RWPs with nonzero phase speed. If that would be true, this would mean that individual RWPs could be accounted for more than once (if they include more than one wavelength) which would further be problematic for the identification of the source of this signal or its overall pattern. Further, how many cases are included in this composite? Shouldn’t it be something like 1-3 events per season (mentioned last page) for this 93 year period? It is therefore somehow surprising that there is such a strong distortion of the wave signal at positive lags. Do the authors have an idea where this is coming from? Concerning the amplification of the signal, is that not a result of the composite for which the RWPs are forced to have equal phasing around day zero, but no such constraints exists for the days before and afterwards, why one would expect the signal to smooth out and decrease in strength.
A: In Figure 10c (IPSL case, -2 lag) there is a statistically significant northerly disturbance over Southeast Asia, which later grows into the RWP itself.
Also, while it is true that the composite phase is not strictly stationary, we make sure to say that the waves have near-zero phase speed. The propagation between figs 10g-10i fits this definition (a few degrees over 3 days).
We agree that the amplification over NA might be an artefact, so we removed this claim from the paragraph. We also now mention the number of RWPs in each composite in the caption for Fig. 10.

R: p.11, lines 340-342: Could the authors explain this more thoroughly how the MM trend (Fig. 4a) can be understood as result of the NA and SA related wave patterns? They add up together to explain the trend given in Fig. 4a? Maybe the authors give some further explanation for the reader.
A: Yes. We now refer the reader to the boxes in Fig. 8 to highlight the specific areas in question.
C: In this light, the spatial structure of the MMM trend can be understood in greater detail. It seems that most anomalous centers can be related to one of the wavetrains that become prevalent in the

projected future in daily data. Specifically, boxes 1-4 (7-9) in fig. 8c correspond to the wave in fig. 10f (10g). Over the Pacific region, it is possible that the North-South dipoles are actually a combination of the two RWP behaviors found in the ensemble (fig. 10g,j).

R: p.11, lines 344-350: What are the implications or the main conclusions here? The main take-away message is that there is a strong jet anomaly upstream of the wave signals? Do the authors have some ideas or hypothesis why the jet should be modified in this way for being able to be associated with a strong wave signal downstream? Nice findings. Do the authors have the information about the connection of their patterns to large scale pattern indices as Fig. 11b looks like a positive NAO (correct?)? Which would be very much in agreement to the findings of Wolf et al (2018, Quasistationary waves and their impact on European weather and extreme events), where they showthat a strong increase in QSW activity along the subtropical jet and the Mediterranean region (EOF2 and 4 in their Fig 11) can be associated with a positive NAO phase. So is the SA group associated with models showing more frequent positive NAO phases? Similar conclusion could be concluded from the PNA, which in its negative phase leads to increased activity of quasi-stationary waves over NA (EOF1 and 3 in Fig 11, wolf et al 2018).

A: We've addressed the NAO connection in the major comments section. As for the local jet modification, at this time we still don't have an explanation for this. This will be the focus of our future work in this project.

R: p.11/12, lines 351-355: This is rather a question, referring again to a point mentioned earlier: are the authors sure about the compositing of RWP events (is there no double counting for lagged RWPs)? Because those double counting with time lags could obscure the temporal relation between tropical forcing and the associated RWP.

A: It is true that the connection to tropical forcing might be obscured (we address this in the Discussion chapter). However, we don't think that double counting is the reason for it. Based on how we define the CTP events, we are confident that phase-propagation in the composite in negligible.

R: p.12, lines 369-370: But this was not working for the projection onto the global CTP, was it? This result was associated with the separation of the signal into different regions. So why can the results be associated with the evolution of the overall CTP? It is not obvious why the results for the analysis, restricted to specific regions, should explain the behaviour of a circumglobal teleconnection pattern. Could the authors maybe make this clearer?

A: As we tried to clarify in the open discussion, we use the term CTP in a broad sense – a class of synoptic, zonal number 5 patterns which also have a clear signature in larger scales (subseasonal, as well as hemispherical). The CTP is fundamentally tied to local scales, as there is no instance of a CTP wave instantaneously encompassing the entire globe. We've tried to stress this point more in the revised version, as seen below:

C:

Line 101 - Despite the "Circumglobal" part of its name, throughout this work we use the term CTP in its most general sense - a class of regional wavenumber-5 patterns, rooted in the synoptic scale while showing a clear signature in the subseasonal range and over the entire hemisphere. Line 67 - This makes the CTP a unique bridge between timescales. The prevalence and quasi-stationary nature of these synoptic RWPs allow their influence to manifest on a subseasonal scale as well. Line 412 - The primary finding of this work is that the majority of GCMs project the CTP to develop a preferred longitudinal phasing over time. While this change is local in nature, its effect is seen on larger scales (both spatially and temporally).

R: p.13, lines 418-420: This link between mean flow (waveguide) and the resulting wave pattern seems indeed crucial. The authors show the spatial relationship which seems to show increased/shifted jet stength upstream of the onsetting wave pattern. Do the authors have some interpretation or insight into the dynamical link for this connection, or is this just a result of increased jet strength (shifted away from) in the locations were are climatologically seen less activity of occurring wave patterns (for those regional wave groups)?

A: See above.

<u>Referee #2:</u>

Major Comments:

R: Are the EOFs for DJF the same as for each month separately? Is there one Month that dominates the seasonal signature? For reference, Ding and Wang 2005 showed that the CTP had different signatures throughout JJA.
A: Monthly EOFs are very similar, for both reanalysis and the MMM. The December EOFs are slightly shifted equatorward, but we do not expect this to impact our results.

R: Could the authors quantify which models have been most accurate in the representation of the CTP compared to reanalysis? In the light of the 'strong disagreements'
A: Added a supplementary plot showing the correlation scores between each model's EOFs and the reanalysis (Fig. S4) between models, this might allow some careful statements which model is more reliable in terms of future projections

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R: Could the authors expand on what intrinsic mid-latitudinal mechanisms might trigger and maintain the CTP and its preferred phase?
A: We mention several mechanisms for CTP excitation in the Introduction section. In the revised version we now delve deeper into the connection between the CTP and the NAO specifically (see subsection 3.4, the Discussion section and Fig. 12). Other possible triggers (like recurving cyclones or stratospheric disturbances) are beyond the scope of our project, and so we focus on NAO and tropical convection.
As for the maintenance of preferred phases, we still don't have an answer unfortunately. As we state in the conclusion of the paper, we will have to explore this question using idealized modelling in the future.

Minor Comments:
R: -Include 'wintertime' in title. Further 'teleconnections' refer to patterns such as 'ENSO' or 'MJO' could this be further specified in the title to avoid confusion? -(p.1, l.2)
A: It is specified that these are subseasonal teleconnections, so there will be no confusion with ENSO or MJO. We added 'wintertime' to the title.

R: '..variability ARE upper tropospheric..' -(p.1,l.4)
A: "is" is referring to "a common feature of…", so this is not a mistake.

R: Others have used the abbreviation CGT (see e.g. Ding &Wang 2005), consider changing CTP to CGT to stay consistent with the terminology used in the literature.
A: This teleconnection has several widely used names, unfortunately. Some use CGT, some use CWP (Haarsma & Selten, 2012; Risbey et al, 2015) and some CTP (Yuan et al 2011, Dai et al 2017). We prefer CTP in order to be consistent with a previous paper (Harnik et al 2016)

R: -Try to avoid effusive / inessential expressions such as 'dramatically' (p.1. l.1), 'surprisingly' (p.1 l.4), (p.3. l.78) and (p.12 l.381), 'first described two decades ago' (p.2,l.25) 'most definitely' (p.14 l.437), 'unsurprisingly' (p.9 l270), 'most definitely' (p.14, l.437)
A: We toned down the language for the given examples: 'dramatically' to 'considerably'; 'surprisingly' to 'seemingly'/'actually'/'unexpected'; 'unsurprisingly' to 'as expected'; 'most definitely' to 'indeed'

R: -Could the authors add a few sentences on differences to summer Circumglobal / stationary waves to the introduction?
C: In this work we focus on the wintertime CTP, but a summertime variant exists as well. In the boreal summer, the NH jet stream shifts poleward and is typically weaker. Therefore, the stationary waves associated with the CTP are shorter in scale (mostly k=6) and lifetime (Teng & Branstator, 2017). Nevertheless, the summertime CTP was also found to be related to extreme weather, such as

heat waves in Southeast China (Wang et al, 2013) or extreme precipitation over western Europe (Saeed et al, 2014).

R: -(p.1, l.4) Maybe change 'likeliness .. emerges' their 'frequency increases' or similar.
A: We mention later in the abstract (where we discuss our results) that RWP frequency increases. However, in line 4 we are posing the question that our work tries to answer – why is it that the trend looks like the CTP.

R: (p.1, l.6) Name the timescales (Monthly and 3-day mean right?)
C: We attempt to elucidate this link across timescales (daily, monthly and climatological), …

R: -(p.1,l.11) 'This categorization strongly corresponds to the ensemble spread in local trend magnitude.' It is not clear to me what this means in this context.
A: Changed the wording to clarify
C: The ensemble is thus divided into subgroups based on region of increased wave activity. For each model, this region corresponds to a more pronounced local trend, which helps explain the ensemble projection spread.

R: -(p.1 l.15) 'Thus, we conclude that this hemisphere-wide climate change signature is actually comprised of several regional effects'. –What hemisphere wide climate change signature? Better use 'response'. Also the authors highlight in the paragraph before, that changes are found visible on a more regional level, how is it a hemisphere-wide signal? Please be a bit more concise
A: The climate response is hemispherical - a single zonal number-5 wave trend. This wave however is a combination of several regional signals. We now reflect this point in the revised abstract.
C: Their likeness seemingly emerges as a robust signal in future meridional wind trend projections in the Northern Hemisphere, which take the form of a zonal wave encompassing the midlatitudes. … Thus, we conclude that this climate change response, seemingly a single large-scale wave, is actually comprised of several regional effects which are related to shifts in CTP phase distributions.

R: (p.1, l.20) 'Projections of future circulation trends, driven by anthropogenic climate change, commonly display large scale patterns.' It feels like this statement requires a reference.
A: Added a reference to the IPCC aAR5

R: (p.1 l.21) '..in order to provide dynamical reasoning and theory.' In order to test hypotheses and theories?
C: Studying these structures in the context of changes in the climatological mean flow is essential in order to understand the underlying basic dynamical mechanisms.

R: p.1 l22.) '..development on finer scales?' What scales, higher temporal resolution?
A: Changed to "a higher temporal resolution"

R: (p.1 l22.) 'changes in subseasonal to seasonal fluctuations' – changes in variability or changes in subseasonal circulation patterns?
A: Both are applicable. We believe this can be stated generally as this is just an introductory phrase.

R: (p.2 l.26.) 'term' change to 'pattern'
A: We are referring to the term CTP as describing waves, so "pattern" doesn't work in this context in this sentence.

R: (p.2 and later) The 'CTP' is described as 'a pattern' and then as 'the wave' or and then as 'waves'. Later it is described as 'a class of related patterns', all of them 'waves'. It would be helpful if the authors could rewrite that part while being more precise in terminology. The sentence in l. 37 should come a bit earlier to clarify the hierarchy among the terms, which are seemingly used synonymous earlier in the paragraph.
A: We changed the phrasing to better indicate that we are talking about several possible waves ('the wave circumscribes' was changed to 'each wave circumscribes'), and also moved up the sentence regarding the CTP being a class of patterns.
C: The term describes quasi-stationary Rossby waves in the upper-troposphere, which are zonally oriented and span the Northern and Southern Hemispheres (NH and SH respectively). On a

subseasonal scale, one can picture the CTP as a "family" of related patterns, all of them waves with an arbitrary longitudinal phase. As they are quasi-stationary …

R: (p.3. l70) is it an acceleration or a poleward shift (or both)?
A: Simpson et al are specifically referring to the acceleration of the jet (larger mean U).

R: (p.23, l.74) works -> studies
A: Changed 'works' to 'studies'

R: (p.3 l.79) please further specify what the conceptual gap is.
C: There is a conceptual gap that complicates the establishment a direct causal link between the CTP and the wavy number-5 trend found in climate change projections. Namely, how do changes in jet driven subseasonal variability translate to long-term climatological shifts?

R: (p.4 l.98) do the patterns depend on the chosen mid-lat range?
A: No. You can choose a narrower range and you will get the same pattern.

R: (p.4 l.105) this sentence seems grammatically wrong?
A: We find no grammatical mistakes in this sentence.

R: (p.5 l. 143) over which years is the climatology defined for reanalysis datasets?
A: We don't present monthly deviation projections for reanalysis, so we don't define a climatology for it

---

R: p.5 l. 148 ff)Wouldn't a negative projection score mean a preferred phase opposite to the one in question while a score of zero would refer to an arbitrary phase?
A: A negative projection score is indeed the antiphase, but a zero score doesn't tell us anything about the phase since the data might not even look like a wave. We explain this point in the revised version
C: Zonal number 5 patterns will have a large absolute score (1 for a perfect copy, -1 for the same wave in antiphase), and a zero score represents some flow unrelated to the CTP.

R: (p.6 l.159) why is a running mean of three days chosen?
A: We wanted to smooth out some noise out of the daily data and chose a window that is shorter than the average CTP lifespan. Our results are not sensitive to this choice.

R: (p.6 l.163) 'future' (p.6 167) ; (p.9 l.264) future , past
A: These are referring to periods we named 'Future' and 'Past', so we capitalize it throughout

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R: (p.6 167) OLR – provide full expression before using an Acronym, here: outgoing longwave radiation?
A: fixed

R: p.6 l171) What are the signatures of the other EOFs? Are they more
local and excluded from the analysis for that reason?
A: Some of the EOFs are some phase shifted version of the circumglobal wave and others are a combination of smaller-scale waves. They are excluded from the analysis since they explain very little of the variability (single digit lambdas).

R: (p.7. l. 220) Please be more specific, I don't understand this sentence.
C: In order to confirm that the regional EOFs are more suited for describing the trend, we calculated how much of its spatial variance was explained by the EOFs (Fig. 4). This was done individually for every model, as well as for the multi-model mean (using composite EOFs and the MMM trend). For most models used, the variance is spread quite evenly across the first five EOFs …

R: (p.9 l.275) what is meant by temporal frequency here, their occurrence on subseasonal timescales?
A: Yes. The stationary signature in monthly data is the average of multiple RWPs, so we don't know when they occur.

R: p.9 l.281) can this statement be quantified?
A: Added the daily-monthly preferred phase difference
C: The daily phase preferences are close to the monthly ones in terms of angle ($|phi_{day}-phi_{mon}|<pi/4$)

R: (p.9 l.286) as a three-day running mean was applied it is incorrect to speak of days in this context. Better use 'timestep' or similar.
A: Changed 'days' to 'daily timesteps'

R: (p.10. l.288) How are events filtered?
A: Added an explanation in the supplementary materials
C: We define "CTP events" in daily mean data. … Two consecutive sequences that are not separated by at least 48 hours are considered one CTP event. Our results were not found to be sensitive to the choice of these parameters. This method of filtering results in some false positive matches. We therefore further filter out all sequences whose composite does not display a wavy signature (alternating mean negative-positive-negative anomalies in the boxes marked in Fig. 8c).

R: (p. 10 l. 290) change 'observational' to 'reanalysis' (here and everywhere else)
A: Changed to 'reanalysis' where relevant

R: (p.10 l. 299) 'much along the lines' -> similar to
A: This is a stylistic choice. We believe the intention is clear in this sentence

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R: (p.11 l.340) The conclusion is hard to understand, could this be re-formulated?
A: Rephrased the conclusion and added a reference to Fig 8 to highlight specific regions
C: In this light, the spatial structure of the MMM trend can be understood in greater detail. It seems that most anomalous centers can be related to one of the wavetrains that become prevalent in the projected future in daily data. Specifically, boxes 1-4 (7-9) in fig. 8c correspond to the wave in fig. 10f (10g). Over the Pacific region, it is possible that the North-South dipoles are actually a combination of the two RWP behaviors found in the ensemble (fig. 10g,j).

R: In the Discussion / Conclusion section: Could the authors provide the Figures in which each of the discussed findings is shown?
A: Added figure references in this chapter

R: (p.12 l.363) change 'business as usual' to 'high emission'.
C: the latter represented by the high emission RCP8.5 scenario

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R: (p.12 l.364) what does 'decent skill' mean in this context?
A: This means that most models capture the centers of action of the wave and the general phase of the leading EOFs but the patterns are not identical to reanalysis. Therefore, we can at least talk about a CTP phenomenon in each model

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R: (p.12 l.369) add a short statement on consquences for predictability / future surface weather.
A: We briefly mention the possible effects on regional precipitation in lines 430-435. We now added some more detail to highlight this issue. On predictability we don't have a statement to add to the conclusions.
C: It is left for future works to examine the possible relations between the CTP and these regional precipitation trends in CMIP models. However, we hypothesize that these results would have implications on surface weather, due to the presence of these recurring, persistent types of flow.

R: (p.12 l.379). Where are those regions?
A: Added the increased initiation areas.
C: … such as areas of prominent RWP initiation (North Atlantic, and the Western and Central Pacific)

R: (p.12 l.383) Reference?
A: Which sentence should be referenced? The statement 'Both are associated with regional precipitation anomalies over their respective domains' is based on the two citations in the previous sentence.

R: (p.12 l.385) 'Seemingly'? Does it or doesn't it?
A: We can't positively say that there is or isn't a contradiction, but we are raising this as a hypothetical issue and immediately after say that future work will be done on the subject.

R: (p.13 l.397) 'However: : :' I don't understand this sentence.
A: We moved this sentence to the next paragraph and rephrased it to be clearer

C: However, the relationship between seasonal, subseasonal and synoptic timescales is not straightforward.

R: (p.13, l.406) Another important scale is the spatial one'. Consider removing this sentence.
A: Removed the sentence and joined the two paragraphs together.

R: (p.14 l.435) 'There is difficultie in singling out..' Could the authors be more specific?
A: Rephrased to make It clearer
C: The CTP is only one mode of many which influence wintertime variability in the midlatitudes, and it's difficult to isolate its underlying mechanisms in the context of a fully coupled GCM.

R: (p.14, l.437) provide reference
A: Added a citation of Teng & Branstator 2017.

R: What else could provide relevant forcing? Consider citing Garfinkel et al. 2020 (https://journals.ametsoc.org/doi/10.1175/JCLI-D-19-0181.1?mobileUi=0)
A: This article is very interesting, but it's difficult to adapt their conclusions (that deal with planetary scale stationary waves) to the subseasonal-to-synoptic waves of the CTP. We expanded our discussion of forcing by including the link between NAO phases and CTP-related RWPs (see Section 3.4 and the Discussion chapter for more detail).

Future Wintertime Meridional Wind Trends Through the Lens of Subseasonal Teleconnections

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Abstract. Large-scale atmospheric circulation is expected to change dramatically considerably in the upcoming decades, and with it, the interaction between Rossby waves and the jet stream. A common feature of midlatitude wintertime variability is upper tropospheric quasi-stationary number-5 wave packets, which often propagate zonally along the jet. These are collectively referred to as the Circumglobal Teleconnection Pattern (CTP). Their likeness surprisingly seemingly emerges as a robust signal in future meridional wind trend projections in the Northern Hemisphere, which take the form of a zonal wave encompassing the midlatitudes.

We attempt to elucidate this link across timescales , (daily, monthly and climatological), focusing on wave propagation in the jet waveguide in observations reanalysis and a 36-member ensemble of CMIP5 models. Using EOF analysis on 300 hPa subseasonal V anomalies, we first establish the ensemble's skill in capturing the pattern. Then, by investigating EOF phase space, we characterize the CTP's behavior in present day climatology and how it is projected to change. Under RCP8.5 forcing, most models develop a gradual preference for monthly-mean waves with certain longitudinal phases. The ensemble is thus divided into subgroups based on region of increased wave activity. This categorization strongly corresponds to the ensemble spread in local trend magnitudeFor each model, this region corresponds to a more pronounced local trend, which helps explain the ensemble projection spread. Additionally, in two test-case models, this coincides with an increasing number of preferably phased wave packets at the synoptic scale. Some signs suggest that differences in CTP dynamics might stem from mean flow biases, while no evidence was found for the role of tropical diabatic forcing.

Thus, we conclude that this hemisphere-wide climate change signature climate change response, seemingly a single large-scale wave, is actually comprised of several regional effects , partly which are related to shifts in CTP phase distributions. The strong dynamical disagreement in the ensemble then manifests as significantly different circulation trends, which in turn might affect projected local temperature and precipitation patterns.

1 Introduction

Projections of future circulation trends, driven by anthropogenic climate change, commonly display large scale patterns (Collins et al., 2013). Studying these structures in the context of ~~shifts~~ changes in the climatological mean flow is essential in order to ~~provide dynamical reasoning and theory~~understand the underlying basic dynamical mechanisms. However, as some signals follow oscillating intrinsic modes (Branstator and Selten, 2009), there are certain benefits to tracing their transient development on ~~finer scales~~a higher temporal resolution. Namely, tracking changes in subseasonal-to-seasonal fluctuations that might have important societal impacts for certain regions.

One example of such a pattern is the Circumglobal Teleconnection Pattern (CTP)~~. First defined less then two decades ago~~ , first defined by Branstator (Branstator 2002, hereafter B02)~~, this~~ . The term describes quasi-stationary Rossby waves in the upper-troposphere, which are zonally oriented and span the Northern and Southern Hemispheres (NH and SH respectively). On a subseasonal scale, one can picture the CTP as a "family" of related patterns, all of them waves with an arbitrary longitudinal phase. ~~The waves are also equivalent-barotropic in nature.~~ As they are quasi-stationary and equivalent-barotropic, this means that lobes of anomalous meridional flow with near-zero phase velocity can prevail over specific regions for several days, sometimes inducing extreme weather such as cold spells (Harnik et al., 2016) and precipitation extremes (Feldstein and Dayan 2008; Teng and Branstator 2017).

~~The~~ Each wave zonally circumscribes the globe along a narrow latitudinal band in the area of the climatological tropospheric jet stream, which serves as its waveguide. The characteristics of these waves (such as scale and amplitude) vary between different regions and seasons (Branstator and Teng, 2017). They are locally determined by the interplay of the jet, its perturbations and at times remote diabatic forcing, most notably in the form of tropical convection (Yasui and Watanabe 2010; Yuan et al. 2011). Through linear Rossby wave theory, one can show that the wintertime (December-February, DJF) boreal waveguide favors stationary number-5 waves, which are at the center of the CTP definition.

~~On a subseasonal scale , one can picture the CTP as a class of related patterns, all of them number-5 waves with an arbitrary longitudinal phase. These patterns are constructed with the linear combination of the two leading~~ In this work we focus on the wintertime CTP, but a summertime variant exists as well. In the boreal summer, the NH jet stream shifts poleward and is typically weaker. Therefore, the stationary waves associated with the CTP are shorter in scale (mostly $k = 6$) and lifetime (Branstator and Teng, 2017). Nevertheless, the summertime CTP was also found to be related to extreme weather, such as heat waves in Southeast China (Wang et al., 2013) or extreme precipitation over western Europe (Saeed et al., 2014).

One method commonly used for isolating these patterns is Empirical Orthogonal Functions (~~EOFs)~~ EOF) analysis. In B02, the author calculated the two leading EOFs of the subseasonal anomalies of monthly 300 hPa meridional wind ~~(~~for the entire NH. This means that each season's mean was removed from every monthly mean V map. The resulting patterns, a pair of rather similar number-5 waves in quadrature, were found to be very robust. B02 ~~)~~showed that they can be produced from different fields' EOFs, as well as other methods altogether (like one-point correlation). Further explanations of the EOFs used in this study are provided in Sections 2 and 3.1.

Mathematically, the subseasonal manifestation of the CTP is constructed from the linear combination of the two leading V EOFs:

$$\boldsymbol{P}(\gamma) = \cos(\gamma)\boldsymbol{V}_{EOF1} + \sin(\gamma)\boldsymbol{V}_{EOF2} \tag{1}$$

Where γ signifies the phase for the resulting wave pattern $\boldsymbol{P}$. This simple deconstruction captures the longitudinal CTP phase, which is an important yet often overlooked characteristic. In B02, regional EOF analysis was performed in order to determine the frequency and teleconnectivity of differently-phased waves. It was concluded that the waves have no preferred longitudinal phase, meaning that combinations of the patterns have a uniformly distributed probability distribution function (PDF). This result was later expanded upon in a 1800 year global climate model (GCM) preindustrial control run (Teng and Branstator, 2017).

Another useful perspective for CTP analysis is through Rossby wave packets (RWPs). These RWPs, sometimes called wave trains, are local ~~structures~~ synoptic structures. The ones that are associated with the CTP are typically comprised of one or two wavelengths, seen as ~~pairs~~ a sequence of troughs and ridges in geopotential height, or as alternating northward-southward anomalies in meridional wind. ~~The RWPs that are associated with the CTP~~ One noteworthy feature of these specific RWPs is their velocity. They have positive zonal group velocity and near-zero phase velocity. So while their centers of action remain almost stationary, the envelope propagates eastward along the jet. This creates the impression of new stationary troughs/ridges appearing downstream of the original RWP, dubbed "downstream development" (Orlanski and Chang, 1993).

~~The~~ This makes the CTP a unique bridge between timescales. The prevalence and quasi-stationary nature of these synoptic RWPs allow their influence to manifest on a subseasonal scale as well. The interpretation of the CTP as the mean signal of many RWPs was suggested by Watanabe (2004), who examined the packets generated after ~~NAO~~ North Atlantic Oscillation (NAO) events in both interannual and intraseasonal time scales. Feldstein and Dayan (2008) later showed the high spatial correlation between RWPs traversing Europe and the Mediterranean and the leading global V EOF, calling the former "a fundamental pattern of variability in the Northern Hemisphere". A similar approach was utilized in Harnik et al. (2016) to link the second global EOF to RWPs crossing the Pacific to North America.

Multiple processes can influence the generation and development of RWPs (see section 4b in Wirth et al. 2018). Excitation of a RWP requires, first and foremost, an initial perturbation near the waveguide. These involve either diabatic latent heating (due to mesoscale convective systems, for example) or potential vorticity anomalies (originating from the lower stratosphere or interacting separate waveguides)~~. Observational case studies for these mechanisms can be found~~ , as was explored in Röthlisberger et al. (2016). Specifically, the NAO can act as a precursor to such RWPs, affecting their path and amplitude (Watanabe (2004); Wolf et al. (2018)).

It has been previously posited that the CTP, as a low frequency internal mode, will be ~~easily excitable by future~~excited more frequently in the future, as greenhouse gas (GHG) forcing grows stronger (Branstator and Selten, 2009). Multiple experiments indeed revealed a CTP-like trend in upper tropospheric flows in response to an increase in GHGs. This is true for both the

CMIP3 and CMIP5 ensembles, using multiple runs of a single model (Selten et al., 2004) or a multimodel dataset (Brandefelt and Körnich 2008; Simpson et al. 2016).

Most notably, Simpson et al. (2016) found a robust zonal number-5 wave structure in the 300 hPa eddy meridional wind trend under the RCP8.5 scenario for 35 CMIP5 models. This is accompanied by increased presence of stationary number-4 and number-5 waves at the expense of shorter ones ($k \geq 6$), as well as robust precipitation anomalies over North America. It was determined that mean flow changes, and specifically future acceleration of the jet, were the driving force of this ~~response (this is not necessarily the case for boreal summer, as described in Teng and Branstator 2019)~~scale shift. Wills et al. (2019) expanded upon these results and emphasized the eastward phase shift of wintertime stationary waves caused by the future wavenumber changes. For the summertime waveguide, the driving mechanism might be more complex, as signs show that changes in the diabatic forcing (convective heating, land interactions) play an important role in the amplification of the teleconnection (Teng and Branstator, 2019)).

Some aspects of ~~the CTP-like trend~~ these teleconnection trends are still not well understood, however. Many of the aforementioned ~~works~~ studies highlight the considerable uncertainty in the regional amplitude of the ensemble's response. For example, Simpson et al. show that model differences in present wave amplitude climatology and future jetstream acceleration can together explain 50 % of the intermodel trend variance. Additionally, on the subseasonal scale, the variance of quasi-stationary waves (calculated using 300 hPa zonal V anomalies~~is surprisingly~~) is actually projected to decrease, in an apparent contrast to the seasonal signature (Wills et al., 2019).

There ~~seems to be some conceptual gap separating works that deal with the CTP specifically from those that identify and analyze~~ is a conceptual gap that complicates the establishment a direct causal link between the CTP and the wavy number-5 trend found in climate change projections. Namely, how do changes in jet driven subseasonal variability translate to long-term climatological shifts? In this paper, we aim to elucidate this connection, which spans across time scales, between future long-term circulation trends and jet driven natural variability. Despite the "Circumglobal" part of its name, throughout this work we use the term CTP in its most general sense - a class of regional wavenumber-5 patterns, rooted in the synoptic scale while showing a clear signature in the subseasonal range and over the entire hemisphere.

We hypothesize that the robust wavenumber-5 climate signal is brought about changes in the waves that comprise the CTP. It is then possible that the key to understanding the trend lies in the statistics and dynamics of wave propagation in the jet waveguide, most crucially at the synoptic and subseasonal scale. These shorter temporal scales might also imply that this hemisphere-wide climate change signature is actually made up of several different regional effects.

After providing data descriptions and definitions (Section 2), we address the issue of how well the CMIP5 ensemble captures the CTP (Section 3.1). Then, we characterize the CTP's behaviour in present day climatology and how it changes as GHG forcing intensifies throughout the 21^{st} century in Section 3.2. After differentiating distinct CTP responses in the ensemble, we compare model subgroups and daily resolution test cases (Section 3.3) in order to better understand the causes and nature of these changes to the pattern. This is followed by discussion and conclusions in Section 4.

2 Data and methods

2.1 Observational data

In order to estimate how well the CMIP5 ensemble captures the CTP, we first turned to ~~observations~~reanalysis. The analysis is performed using monthly and daily mean data from the National Centers for Environmental Prediction I (NCEP-I; Kalnay et al. 1996) and ERA-Interim reanalysis (Dee et al., 2011) datasets. We focused on the winter season of December to February (DJF), between 1958-2015 for NCEP-I and 1979-2014 for ERA-Interim. For direct comparison, the ERA-Interim data (as well as all CMIP5 model output described later) was interpolated to fit the NCEP-I $2.5° \cdot 2.5°$ horizontal grid. Unless stated otherwise, the circulation is examined in the 300 hPa meridional wind field (V) between $10° - 85°N$.

Following B02, we generated meridional wind EOFs using monthly subseasonal anomalies of V, meaning that each winter's DJF mean was removed from its monthly mean V fields. Subseasonal anomalies are used in order to negate large scale interannual signals (driven by SSTs for example) which otherwise dominate the EOFs. Meridional wind is chosen instead of streamfunction or geopotential in order to better capture zonally elongated, smaller scale patterns such as the CTP (see Appendix A in Branstator and Teng 2017). While B02 uses non-divergent V, we employ the full field. As noted in Harnik et al. (2016), this does not not affect the resulting patterns.

As for the spatial domain, "global" EOFs are calculated using all longitudes; and regional EOFs are based on $144°$ longitudinal sectors (roughly equals two number-5 wavelengths). The Euroasian domain (denoted as AS) spans $0° - 144°E$, and the Pacific North American (NA) domain covers $180° - 324°E$. These particular regions were chosen due to their position right downstream of areas in the North Pacific and Atlantic oceans with considerable Rossby Wave Packet activity during winter months (Souders et al. 2014; Röthlisberger et al. 2018). The EOF analysis was employed on these domains separately (as opposed to simply using sectors of the global EOFs) in order to preserve the orthogonality of the functions. Harnik et al. (2016) showed that the regional patterns are well matched with the corresponding sector of the global ones.

2.2 CMIP5 runs

For model data, we use simulations from 36 GCMs in the CMIP5 ensemble (Taylor et al. 2012; for the full list of models used, see supplemental data). Monthly mean flow fields (meridional and zonal wind) are analyzed for all models on the 300 hPa level, similar to ~~observations~~the reanalysis data. We also investigate these fields (as well as 250 hPa horizontal divergence and outgoing longwave radiation) in the daily resolution for two models (IPSL-CM5A-MR, MIROC-ESM-CHEM) as representative test cases for the two dominant types of climate responses that were observed in the ensemble. The daily mean flow, however, is taken from the 500 hPa level, as 300 hPa data was not publicly available for these daily runs. A comparison between the two levels (not shown) reveals that the two are adequately similar in terms of the EOFs and associated CTP circulation. This is to be expected, as the CTP is considered an equivalent-barotropic phenomenon.

All models are examined under the Historical and RCP8.5 scenarios. Historical runs span the period between 1900-2005 in the monthly resolution and 1950-2005 for daily means. RCP8.5 runs are between 2006-2099 for all temporal resolutions. For one daily data test case (IPSL-CM5A-MR), a longer Pre-industrial Control run was also used (1800-2100). The EOFs for every model were produced in a similar manner to ~~observations~~ the reanalysis datasets (for the hemispherical and two regional domains), using Historical data only. For the most part, longer datasets are preferable for this type of calculation. However, we opted to exclude Future data (2006 and onward). This allows better comparison between models and ~~observations~~reanalysis, while also keeping the distinction between the studied pattern and the projected climate signal which might affect its behaviour.

2.3 Pattern correlation and EOF phase space

Pattern correlation is used extensively throughout this work as a tool for comparison between models and observations, and for projection scores on the EOF phase space (as explained below). We calculate the Pearson correlation coefficient for two maps, each weighted by the square root of cosine latitude. It is important to note that this measure is useful in assessing pattern similarity and phase difference, but does not reflect amplitude differences (for matrices $\boldsymbol{A},\boldsymbol{B}$ and scalar c, $PCC(\boldsymbol{A},\boldsymbol{B}) = PCC(\boldsymbol{A},c\boldsymbol{B})$).

We define the CTP as any linear combination of the leading two EOFs, encompassing all phases. Therefore, in order to quantify how "CTP-like" a certain flow pattern P is, we construct a phase space based on EOF1 and EOF2. The complex projection score of map $\boldsymbol{P}$ is thus $PCC(\boldsymbol{P},EOF1) + iPCC(\boldsymbol{P},EOF2)$, revealing both the level of similarity between the flow and the CTP, and the longitudinal phasing of the pattern. The former corresponds to the modulus of the projection score and the latter to its argument (Fig. 1).

The question of what kind of data to project on the EOF phase space is not a trivial one. For the daily time scale, the progression of Rossby wave packets can be properly captured by the full V field, achieving projection scores of 0.5 and higher. Additionally, the CTP is essentially a subseasonal phenomenon and is thus expected to have a signature in data with longer timescales as well. Nonetheless, full field monthly data projections generally fall short in terms of pinpointing the pattern. This might be due to planetary-scale stationary waves which are more prominently featured on those timescales. We thus use V anomalies, or deviations from a 30 year climatology. Considering that the climatology is itself changing throughout our experimental period (from pre-industrial times to the late 21^{st} century), we chose early 20^{th} century (1900-1930 DJF mean) as a representative reference period, which we then remove from the monthly mean V field. Our results were found to be insensitive to the selection of climatological time span.

~~We average all highly projected monthly index values to obtain the mean projection score of every experimental run. This is done after~~ After excluding data with low projections scores (below the 70^{th} percentile of index magnitude), ~~as these months' phase index doesn't have physical meaning. Our results are not sensitive to the choice of percentile threshold~~we average all remaining monthly values to obtain the mean projection score of every experimental run. Patterns with an overall arbitrary phasing will have oppositely signed monthly scores cancelling each other, and therefore a mean projection close to the origin. When a model's mean score exceeds the RCP8.5 Multi-Model Mean (MMM) projection score by one standard deviation, it is considered to have a "preferred" phase. A model subgroup, used for trend and forcing comparisons, is defined by all models whose preferred phase over a geographical domain (NA or AS) occupy the same half-plane on the phase space.

Statistical significance of group composites is determined by a sign test, which indicates where a certain percentage of group members have the same sign as the composite mean. The chances for a given percentage of events to have the same sign as the composite mean are determined using a binomial formula, assuming equal chances for positive and negative anomalies.

2.4 CTP events

We define "CTP events" in daily mean data, which are essentially a synoptic manifestation of the wave patterns that are found in monthly data. We capture quasi-stationary Rossby wave packets that are in the same domain and . These are essentially Rossby Wave Packets that are nearly in phase with the preferably phased monthly patterns (only on the 500 hPa level, as explained previously). To do so, we first equivalent of the preferably-phased pattern that was found in the 300 hPa monthly projections. First, we apply a 3-day running mean on the 500 hPa daily V field. After calculating the projection index and excluding low values (as in the monthly case), we detect all sequences of three or more consecutive days in which $|\gamma_d - \gamma_m| \leq \pi/8$, where γ_d and γ_m $|\phi_d - \phi_m| \leq \pi/8$, where ϕ_d and ϕ_m are the daily and preferred-monthly phases respectively.

When creating wave composites, we remove the Future climatology (2070-2099) from the daily means in order to observe wave propagation and to remove the signature of other low frequency patterns. Lag 0 of a CTP event is defined as the first day of the sequence and statistical significance is determined by a 1000 member bootstrap method.

To test the NAO's possible role in forcing the CTP, we use a standard NAO index (Hurrell et al., 2003): projection of monthly sea-level pressure (SLP) anomalies onto the leading EOF of the seasonal SLP anomaly in the North Atlantic sector ($20°N - 70°N; 90°W - 40°E$). Positive and negative NAO phases are defined as months when the index exceeds one standard deviation ($\pm\sigma$).

Additionally, we used lagged linear regression (Livezey and Chen, 1983) of outgoing longwave radiation (OLR) and upper tropospheric divergence, in an attempt to establish a causal relationship between tropical convective forcing (expressed by OLR and upper tropospheric divergence) and and the excitation of CTP events. However, the resulting patterns were not statistically significant, hence additional technical details are only provided in the supplementary materials.

3 Results

3.1 Representation of the CTP in the CMIP5 ensemble

The CTP can be obtained by calculating the first two leading EOFs of the monthly winter (DJF) subseasonal anomalies of the upper-tropospheric meridional wind. The observational patterns for NCEP-I reanalysis can be seen in Fig. 2. Very similar patterns were also produced from ERA-interim data (not shown).

In both cases, the set of EOFs is comprised of two quasi-stationary zonal number 5 waves which are in quadrature with one another. They explain 13.6 and 10.8 % of the variance (denoted by λ) in the NCEP/NCAR dataset, and 13.3 and 11.5 % in ERA-Interim. For ERA-Interim, the two EOFs are not well-separated from one another (as well as from the third EOF) according to the definition set by North et al. (1982). For NCEP-I, a longer dataset, the patterns are well-separated.

Performing the same calculations on 36 GCMs from the CMIP5 ensemble reveals the robustness of this pattern. In order to allow a comparison to observational present-day climate, the monthly data used in calculating the EOFs came from historical model runs only (between the years 1900-2005). We base all of our calculations and projections hereafter on the historical EOFs, even when working with data from Future runs, as no considerable differences were found in EOFs based on RCP8.5 data (not shown).

Figure 3 demonstrates the strong agreement between models in regards to the main features of the CTP (for every individual model's EOFs, see supplementary Fig. S1). Most notably, almost every model has zonal number 5 waves in their two leading EOFs, with a stronger amplitude above North America and correctly phased patterns. As expected from theory, the waves are latitudinally confined to the area of the climatological jet stream. However, it is worth noting that model agreement on the first EOF is more robust, and that it is also closer to the ~~observational~~ reanalysis-based function, as will be demonstrated quantitatively.

For most models, the variance explained by these patterns is slightly higher than in ~~observations~~reanalysis, with median ensemble values of 14.8 % for the first EOF, and 10.7 % for the second. Around two thirds of ensemble members have well-separated EOFs as well, with EOF2 separated from both the first and third functions in most cases. This might be a result of the model runs being almost twice as long (105 winters) as the observational records (57 winters in the longer dataset, NCEP-I).

In order to quantify each model's skill in representing the CTP, each set of two EOFs was projected onto the observational patterns with cosine latitude weighting. Most models can reproduce the spatial features of the CTP fairly well. ~~With a score of~~ Zonal number 5 patterns will have a large absolute score (1 ~~representing~~ for a perfect copy, ~~the~~ -1 for the same wave in antiphase), and a zero score represents some flow unrelated to the CTP. The ensemble has a median score of 0.78 and 0.5 for the first and second EOFs respectively. There is however a larger spread in skill for the second function.

3.2 Changes in CTP behavior in a warming world

3.2.1 Projecting the MMM climate trend onto the EOFs

A quasi-stationary zonal number 5 wave in the northern hemisphere appears to be a prominent feature of the projected circulation ~~response to GHG forcing~~trend in high emission scenarios. The similarity between the CTP and CMIP5 future circulation trends has been noted before (Brandefelt and Körnich 2008; Branstator and Selten 2009; Simpson et al. 2016). However, to our knowledge no effort has yet been made to objectively link the two based on the EOF perspective that was used by B02 to first define the CTP.

Under scenario RCP8.5, the multi-model mean response in the 300 hPa meridional wind indeed takes the form of a number 5 wave globally (Fig. 4). This response being the Future climatology (2070-2099) minus the Past climatology (1979-2005)~~.~~ ~~Nonetheless, when~~, similar to the one analyzed in Simpson et al. (2016). Despite the apparent similarity, the pattern itself is not a pure combination of the global EOFs. When projecting each model's trend onto its historical EOFs, one gets rather low scores (absolute mean of 0.24 and 0.21 for EOF1 and EOF2).

In order to further test this point, we calculated how much of the trend's spatial variance was explained by the EOFs (Fig. 4). This was done individually for every model, as well as for the multi-model mean (using composite EOFs and the MMM trend). For most models used, the variance is spread quite evenly across the first five EOFs (the higher-ordered of which have lower λ values). In particular, the first two leading functions, which define the CTP, explain less than half of the trend's variance for 26 of the 36 ensemble members. As for the two leading composite EOFs, they account for only 0.8 % of the MMM trend variance, while the majority is explained by the third and fourth composite functions.

This issue can be somewhat solved by dividing the trend into different regions. By doing so, we can inspect whether separate longitudinal sectors in the northern hemisphere develop different CTP-like responses. The regions used, as elaborated in Section 2.1, are Pacific-North America (NA) and Euroasia (AS), each spanning 144° longitudinally, or approximately 2 wavelengths (see boxes in Fig. 4a). Calculating the EOFS EOFs anew, as opposed to using segments from the global ones, makes sure that the functions remain orthogonal (the MMM regional EOFs are presented in supplemental Fig. S2). As was the case for the global EOFs, the regional EOFs display a good resemblance to their observational counterparts, both in qualitative structure and pattern correlation score (not shown).

In order to confirm that the regional EOFs are more suited for describing the trend, we calculated how much of its spatial variance was explained by the EOFs (Fig. 4). This was done individually for every model, as well as for the multi-model mean (using composite EOFs and the MMM trend). For most models used, the variance is spread quite evenly across the first five EOFs (the higher-ordered of which have lower λ values). In particular, the first two leading functions, which define the CTP, explain less than half of the trend's variance for 26 of the 36 ensemble members. As for the two leading composite EOFs, they account for only 0.8 % of the MMM trend variance, while the majority is explained by the third and fourth composite functions.

When looking at the spatial variance explained by the MMM regional EOFs (Figure 4c-d) one can see thatfor many models, they are more suited for the description of the MMM , for the majority of the ensemble, they are better at describing each model's trend. The ensemble median value for the variance explained by the first two leading functions is 61 % for the NA region and 56 % for AS. This is almost twice as the median for the global EOFs, which explain 32 % of the trend. This allows us to use only these regional functions for our analysis (two EOFs for each region).

This improvement might seem unexpected, considering the spatial similarity between the global and regional EOFs (see Fig. S2 in the supplementary material). However, this is by virtue of the added degrees of freedom (an index consisting of four regional projections, instead of two global ones).

3.2.2 Emergence of preferred phasing in monthly data

With some association between the trend and the CTP established, it is important to understand the temporal development of this signature. The data being used in this section is the monthly DJF 300 hPa meridional wind, for both Historical and RCP8.5 runs in each model. The Historical run spans from 1900 to 2005, and RCP8.5 from 2006 to 2099 (adding up to 315 and 279 months, respectively). From these maps we then remove the pre-industrial winter climatology (1900-1930).

Using the EOF1-EOF2 phase space thus reduces the relation between each month and the CTP into common two dimensional vector parameters - magnitude (Euclidean norm of both projection scores) and angle. The former reveals how much does each month resemble the CTP and the latter signifies what longitudinal phase it has.

For the projections, we use the two sets of regional EOFs. After removing months with low projection scores, we examine the remaining distribution across the phase space, and also compare it to NCEP-I data. For all 36 models, historical data is spread approximately uniformly on the phase space (blue dots in Fig. 5, shown for two single model examples), meaning that CTP phasing is arbitrary throughout these runs. This is similar to the spread in reanalysis data (not shown) and previous studies (Teng and Branstator, 2017).

However, this is not the case for the projected future. Under the RCP8.5 scenario, most models show a preference for certain phases, for either the NA or AS regions (or both, in the case of two specific models). This means that the number of winter months that fall within a specific quadrant on the phase space is significantly higher than what would be expected from a uniformly distributed dataset. This trend becomes even more pronounced towards the end of the 21^{st} century. Projections on global EOFs do not reflect these results, but rather remain uniformly distributed throughout all runs (not shown). This is due to the regional scale of the emerging patterns. For example, months with a good resemblance to the North American sector of the CTP might still receive a low projection score due to a lack of wave activity over Euroasia.

The mean location of every model on the phase space illustrates this idea of preferred phasing (Fig. 6). A uniform distribution of monthly projections, centered around the origin, will trivially yield a mean projection score close to zero (as is the case for all Historical CMIP5 runs). In contrast, ~~most models'~~ more than half of the ensemble's RCP8.5 runs have a mean projection score bigger than 1σ for at least one region (σ being the standard deviation of all RCP8.5 mean projection scores). For the NA region, nine models have a majority of months with a positive (negative) time-mean score for EOF1 (EOF2). Eight models display a preference in the AS region, with negative (positive) scores for the regional EOF1 (EOF2). Two additional models show these tendencies for both domains.

Interestingly, we can identify a common phasing that is shared by all strongly projecting models in each region ~~.~~ (in Fig. 6, these are the filled red rectangles which are outside the circle). Specifically, almost all models that have a none-zero mean projection onto the NA phase space concentrate around approximately $\gamma = -\pi/8$. Similarly, seven models with mean projections on the AS EOFs are in and around the second quadrant. This allows us to subjectively define four distinct model subgroups (NA, AS, BOTH, NONE) according to their region of preferred phasing (Table 1). The preferred patterns themselves can be obtained by following Eq. (1).

Members of the NA group have an abundance of months with a ridge located near and off the west coast of North America. Teng and Branstator (2017) noted that there is "a continuum of low-frequency zonal wavenumber-5 patterns" which can produce this structure. The preferred phasing shared by the NA models (a positive EOF1 and a negative EOF2) is indeed included within this continuum. Meanwhile, the AS group's models show a typical monthly anomaly consisting of a strong northerly flow across the Eastern Mediterranean and India, and southerly winds over the Arab peninsula and Southeast Asia. This is quite similar to the positive phase of the Southern Levant (SL) pattern, as defined by Feldstein and Dayan (2008). The combination of these regional flow patterns is very reminiscent of the MMM climate trend, as seen in Fig. 7.

We attempt to clarify the connection between the subseasonal and the climatology by examining the different model subgroups. There is strong agreement within the ensemble in regards to the general structure of the 300 hPa meridional wind trend between the Future and Past periods. However, as previously mentioned, there is considerable spread in the magnitude of the response, with up to a 5 ms^{-1} difference in wave amplitude for some regions.

By dividing the models based on their region of increased CTP activity, significant local differences in the climate trend become apparent (Fig. 8). For every group (other than the NONE group of course), the region with preferably phased waves also shows a stronger trend response. Three areas stand out in particular as sources of disagreement between groups: The AS group has a more pronounced signal over the Mediterranean and South Asia (boxes 1-4 in Fig. 8c) and around the Bering Sea in the northern Pacific (boxes 5-6). As for the NA group, its stronger signal is unsurprisingly found over North America (boxes 7-9), as expected. Fig. 8d illustrates this point, as regional wave amplitudes of the trend differ between model groups. This result expands on Brandefelt and Körnich (2008), who also identified analogous local trend differences in a smaller set of the CMIP5 ensemble.

3.3 The wave packet perspective - CTP in daily data

3.3.1 The daily data phase space

Using monthly data is limiting in terms of analyzing the actual progression of the waves, their duration or temporal frequency. In this section, the dynamics of the waves will be explored using daily mean V data from two members of the CMIP5 ensemble - IPSL-CM5A-MR and MIROC-ESM-CHEM (abbreviated below as IPSL and MIROC). The latter is included in the AS group and the former in the NA group, and both are in the ensemble's top 20^{th} percentile in terms of spatial correlation to observational EOFs.

Using 500 hPa EOFs and daily mean V, we can again calculate projections of the data and get the score and phasing for the Historical (1950-2005) and RCP8.5 (2006-2099) runs. The daily phase preferences are approximately the same as the close to the monthly ones in terms of angle ($|\phi_{day} - \phi_{mon}| < \pi/4$). However, this does not mean that the two timescales capture the same phenomena, as the correlation between the two is non-trivial. This will be further inspected in the Section 4.

3.3.2 CTP events

Next, we define the "CTP event". These events provide a way of capturing the teleconnection in the form of RWPs, as it is manifested in synoptic timescales. Essentially, a CTP event is a sequence of at least three consecutive days daily timesteps with high projection scores and angles close to the preferred mean monthly phasing. These events are defined in relation to a specific region, according to the EOFs used for projection. The list of potential events is further filtered in order to remove false positive matches (for additional details, see Section S1 in the supplementary material).

We first apply this method to observational datasetsreanalysis, with wave phases taken from the CMIP5 subgroups for the NA and AS regions. For the NCEP reanalysis, an average of 1.5 events per season was found in the NA region, and 0.5 events per season in AS. Meanwhile, the ERA-Interim dataset seems to capture more events, with an average of 1.8 and 0.9 per winter for the two respective domains.

~~These results comfortably fall within the range set by Souders et al. (2014) for winter RWP frequency. In their comprehensive climatological study, they tracked $\sim$ 6000 RWPs that appear globally throughout the year. They~~ For comparison, Souders et al. found that, on average, about 11 RWPs form over the Pacific Ocean every winter, while 9 are formed over the Atlantic. ~~Geographically, their domains roughly correspond to our NA and AS regions. Our~~ This was calculated by tracking $\sim$ 6000 RWPs that appear globally throughout the year. Note that the comparison to our results is not straightforward. For instance, a RWP formed in the Pacific might be categorized in both of our groups (depending on its path). Additionally, our CTP events likely constitute only a small subset of this climatological RWP dataset~~(~~, which covers all phases and a wide range of wavelengths~~), making~~. This makes their result serve as a loose upper bound. Another more specific bound can be found in a work by Wolf et al. (2018). The authors examined the climatology of long-lived quasi-stationary waves using the ERA-Interim dataset, and found an average of 0.6 instances per winter (DJF) of waves with a lifetime of 10 or more days. This is more directly related to circumglobal RWPs, which typically require more than a week to complete their path.

In the two GCMs, behavior of the CTP changes between the Historical and RCP8.5 periods, much along the lines of the monthly data results. For IPSL and the NA region, the number of events nearly doubles between the Past and Future periods (from 1.6 to 3 events per winter). In the AS region, MIROC CTP event frequency increases from 1.1 to 1.9 for the same metric. It's important to note that these changes only happen for a narrow range of wave phases (less than a full quadrant) within every model's domain. One interesting exception is found in MIROC, which shows ~~the~~ this trend for both domains, in the daily timescale only. The average lifetime of the wavepackets does not change between the runs, and was found to be 6 and 5.5 days for IPSL and MIROC, respectively.

For both models, the additional events are not evenly spread throughout the RCP8.5 winters, but are rather concentrated in a few seasons with ~~amplified wave activity~~ increased wave frequency (Fig. 9). As the average number of events per winter increases, the tail of the distribution shifts as well. Thus, we begin to see winters with five or more events, which is unprecedented before 2006. Performing the same analysis on a long Pre-industrial Control run (unfortunately available only for IPSL) further underlines how the projected RCP8.5 future differs from unforced natural variability.

3.3.3 RWP propagation

We can mark the first day of each series of CTP days within an event as lag 0 and follow the propagation of the RWPs. By definition, each such lag 0 day has a high projection score on the preferred phase, meaning that the RWP is ~~at the peak of its life cycle~~already past its initial excitation and is at least somewhat developed. By creating a simple composite of all events for each model and domain, we observe the general features of a "typical" RWP, without tracking individual waves.

~~The wave packets all share~~ These composite wave packets (seen in Fig. 10) display realistic characteristics that have been previously affirmed ~~by observations~~ in reanalysis and models (Souders et al. 2014; Röthlisberger et al. 2018; Wirth et al. 2018)~~.~~: They are of synoptic scale and their propagation takes place over the course of ~~several days~~approximately one week. Their centers of action remain fairly stationary throughout, meaning that they indeed have near-zero phase speed. ~~The waves thus~~ This is by construction, as the RWPs were chosen to have persistent strong projections onto the same phase. The waves propagate zonally by downstream development, with a new positive or negative anomaly forming every 48 hours or so. Furthermore, the waves ~~on~~ in both models are excited over regions that have been previously identified as prominent sources for winter RWP activity.

~~Figure 10 shows the lagged composites. For IPSL~~For the IPSL case, the waves' source is located over Southeast Asia. They traverse the Pacific Ocean and on its Eastern coast they project strongly on the positive phase of the Pacific-North American teleconnection (PNA). Similar to the monthly case, this longitudinal section has the strongest response, with an amplitude of up to 5 m s^{-1}. ~~In fact, it seems as though the initial wave packets slow down and are then amplified over North America (lags -2 to +2). This might point to the existence of external forcing or positive feedback that affects the RWPs in this region.~~

On the other hand, the Euroasian waves in the MIROC run originate near the United States. The regional EOF projection captures a mature stage in their propagation, as lag 0 (Fig. 10f) occurs about a week after the initial excitation. Interestingly, this marks only an intermediate point along their near-circumglobal trajectory. After crossing the Atlantic, the composite RWP propagates further across the Pacific and finally projects onto the negative phase of the PNA, near the wave's origin.

Over this region, the later part of the AS-projected wave is in antiphase with the NA-projected one (compare North America in Fig. 10g,j). This might explain why MIROC shows no monthly preferred phasing in the NA region. Despite having the same trend in daily data as IPSL (i.e. more frequent RWPs with $\gamma \approx \pi/8$), this activity is masked by waves of opposite phase when averaging on longer timescales.

Since the composites are based on EOFs (which are also not well-separated), we need to carefully confirm that this circumglobal signature is not just a mixture of different local wave patterns in various stages of propagation. Indeed, over 60 % of individual CTP events have a strong projection (≥ 0.2) onto both early and late stages of the composite propagation (lag -4 and +4, respectively), with significant wave activity across both oceans. Furthermore, Southeast Asia has been found to have far-reaching teleconnectivity, with high point-correlation to centers around the globe (B02). This alludes to the fact that these RWPs might be truly circumglobal.

In this light, the spatial structure of the MMM trend can be understood in greater detail. It seems that most anomalous centers can be related to one of the wavetrains that become prevalent in the projected future in daily data~~- the NA preferred RWP, in addition to the two halves of the circumglobal pattern of the AS group (compare Fig. 4a,10gand 10~~. Specifically, boxes 1-4 (7-9) in fig. 8c correspond to the wave in fig. 10f (10g). Over the Pacific region, it is possible that the North-South dipoles are actually a combination of the two RWP behaviors found in the ensemble (Fig. 10g,j).

3.4 Differences in the mean flow and forcing

While differences in CTP activity might shed some light on the spread in the climate response, the question still remains: What causes these differences in the first place? One element which might allude to the answer is the mean flow. The zonal mean flow, a crucial factor in the propagation of RWPs, displays some variance within the ensemble. It appears that for each group, in both Historical and RCP8.5 runs, the CTP-prone region also has a stronger, narrower mean jet compared to the remaining ensemble mean (Fig. 11). This bias is mostly noticeable over maritime areas, just downstream of the RWP origins. It takes the form of a meridional tripolar pattern around the jet core. For the NA region, this tripole is also evident in the composite daily jet anomaly during CTP events (not shown).

As for other large scale modes which can trigger the CTP, the phase of the NAO was found to be correlated with the occurrence of monthly CTP preferred patterns in the AS region (a pattern similar to the "downstream extension" found in Watanabe (2004)). For seven models of the AS group, we calculated the share of preferably phased Future CTP months to happen concurrently with a positive or negative NAO phase. For six of the seven models, the monthly AS CTP pattern is at least twice as likely to occur with a positive NAO phase (Fig. 12). No such relation was found for preferred NA phases (not shown).

Another useful area of inquiry is the location and magnitude of tropical and subtropical diabatic heating. This forcing can, in some cases, provide the initial perturbation for the excitation of the waves. Hence, recurring heating in a specific area might help explain the abundance of RWPs with certain phases.

However, lagged regression analysis did not reveal a straightforward connection between CTP events and supposed tropical precursors. We calculated these relations for various fields and indices that are indicative of CTP activity, focusing mostly on meridional velocity or the CTP index (phase angle of strongly projected days, index magnitude of preferably-phased days). While some convective patterns emerged (combined negative OLR and positive upper-level divergence; not shown), none were statistically significant. In fact, most tropical gridpoints showed little to no correlation (<0.1) to fields related to CTP Events. This point will be discussed later on.

4 Discussion and Conclusions

In this study we examined how changes in the subseasonal teleconnection variability are linked to long term circulation trends in boreal winter. This was done by identifying and characterizing the CTP in 36 members of the CMIP5 ensemble, comparing present and future climates (the latter represented by the ~~"business as usual"~~ high emission RCP8.5 scenario). The ensemble was found to have decent skill in capturing this pattern compared to observations, in terms of both spatial structure and percentage of DJF variance explained ~~.~~ (Fig. 3).

The primary finding of this work is that the majority of GCMs project the CTP to develop a preferred longitudinal phasing over time ~~, and that the local nature of this~~ (Fig. 6). While this change is local in nature, its effect is seen on larger scales (both spatially and temporally). Specifically, this phase preference strongly corresponds to each model's future trend in meridional wind. This is in contrast to what is known from observations, where CTP phasing seems to change arbitrarily on an intraseasonal basis. This means that for the projected future, a growing number of winter monthly mean flows take the form of a number-5 zonal wave with a specific phase. Additionally, in two studied test cases, this translates to an increasing number of preferably phased RWPs per season ~~.~~ (Fig. 9).

This phase locking occurs on a regional scale, and there is strong disagreement in the ensemble regarding where exactly it will take place. Nine models (NA group) predict an emergence of preferred CTP phasing over the North Pacific and North America, while another 8 have a strong signal over the Euroasian region (AS group). Two more models display some mixture of these responses, and the remaining 17 show no preferred phasing at all. The future trend of meridional mean flow is projected to change accordingly ~~.~~ (Fig. 8). NA models show a localized large-amplitude signal over their region of preferred phasing, while AS models have a nearly circumglobal wave trend with particularly stronger anomalies over Europe and the Mediterranean.

Our results are mostly in good agreement with previous works, which focused on either the pattern itself or on the projected circulation changes. Relevant climatological features of the jet stream waveguide are present in our findings, such as areas of prominent RWP initiation (~~Röthlisberger et al. (2018)~~North Atlantic, and the Western and Central Pacific; Röthlisberger et al. 2018) and specific phases with extended teleconnectivity (Branstator (2002)). In terms of the pattern itself, the two regional responses that we found ~~surprisingly~~ resemble observed local manifestations of the teleconnection, named the South Levant pattern (Feldstein and Dayan (2008)) and the Circumglobal North American pattern (Harnik et al. (2016)). Both are associated with regional precipitation anomalies over their respective domains. As for the SL pattern specifically, its positive phase (which mirrors the CTP trend) is actually linked to increased precipitation over the Eastern Mediterranean. This seemingly contradicts the robust projected drying of the Mediterranean region in the ensemble. ~~It~~ However, it is left for future works to examine the possible relations between the CTP and these regional precipitation trends in CMIP models. Nevertheless, we hypothesize that these results would have implications on surface weather, due to the presence of these recurring, persistent types of flow.

As for the relevant climate change literature, we believe our phase-centered approach extends and contextualizes previous results. The MMM V trend seen in Simpson et al. (2016) is reproduced in our analysis. Their work analyzes the conditions which drive the differences between present and future climatology, while our results "fill the gaps" and explore how these processes manifest on a subseasonal scale. A major finding of their work relates the MMM trend to a shift to longer zonal scales for stationary waves. While the strongest response happens in number-4 waves, they also present a robust signal (over 75% of ensemble members) for number-5 waves. This might be related to a stronger mean CTP signature brought about by the narrower distribution of phases.

This brings up an interesting question on the relation of different scales in stationary waves. Heuristically speaking, it's useful to think about this problem as mere downscaling - the MMM trend as an averaging of many CTP-like months, which are comprised themselves of synoptic-scale Rossby wave packets. ~~However, a more rigorous examination will reveal that the~~ However, the relationship between seasonal, subseasonal and synoptic timescales ~~are not fully interchangeable.~~ ~~This is very~~ is not straightforward. This is effectively demonstrated in Wills et al. (2019), who actually found a projected decrease in subseasonal (or rather monthly) meridional wind variance in the NH midlatitudes. It is pointed out that this seemingly contradicts the expected enhanced signature of quasi-stationary waves. This apparent discrepancy was also revealed in our results, as we found that seasons with a high number of wave packets don't necessarily receive a high projection score in monthly data, and vice-versa. This results in only a moderate positive correlation (0.4) between the seasonal monthly projection score and the number of wave packets every season. Wills et al. cite the accelerated advection of Rossby waves as a possible reason for the inconsistencies, as their signature is smoothed out on longer timescales. ~~Since there is a strong connection between the extent of a RWP's path and velocity, this reasoning fits well with the increased occurrence of nearly circumglobal wavepackets presented here.~~

Another important scale is the spatial one. The CTP is most commonly observed and analyzed from a hemispheric point of view, and yet GCMs predict significant regional differences in wave behavior under GHG forcing. The different local trends identified in Brandefelt and Körnich (2008) partially match our categorization of NA and AS trends in the ensemble. They too noted that differences between GCMs (CMIP3 members in this case) span either the North Pacific and North America, or the Atlantic and Euroasia.

A comparison can be made, to a certain degree, between the model groups and trends shown in this work and by Brandefelt and Körnich. Specifically, in both works, models from the GISS and MIROC centers were found to have a similar "Euroasian" response - poleward anomalies over western Europe and the Arab Peninsula, and equatorward ones over eastern Europe and India. There is little in common for other ensemble subgroups. This is unsurprising for several reasons. Other than the obvious difficulty of comparing ensembles from different generations, the approach used to define subgroups is quite different - "bottom-up" (subseasonal EOF projections) versus "top-down" (trend similarities).

One major issue that still remains mainly unresolved is what causes CTP phase distributions to change. We believe that understanding what drives the two very different projected CTP signals (NA and AS) might shed some light on this topic. We found significant differences in the mean flow between model groups. When compared to the ensemble mean, a group with phase preference was found to have U biases over the relevant domain, even in the Historical climatology. Specifically, a stronger and narrower jet was identified over a sector spanning roughly one wavelength and located just downstream of RWP initiation area. Often it is difficult to differentiate mean flow properties from the resulting transient patterns. However, since this jet difference was found in the Historical model biases (and not in the trend itself), it alludes to a possible causal mechanism which affects the CTP.

It has been well established that such mean flow features play an important role in determining the scale and amplitude of stationary waves (Simpson et al. 2016; Branstator and Teng 2017). As far as phasing is concerned, certain longitudinal phases have longer reaching teleconnectivity (Branstator (2002)). One interpretation of our results includes a combination of both aspects. It is possible that certain local configurations of the jet stream trap longer lived RWPs from a narrow range of phases. While the overall projected strengthening of the jet leads to a robust CTP-like response across the ensemble, it is regional biases in the zonal flow which account for the model spread.

Large scale internal modes also act as forcing for the CTP. The monthly AS pattern, specifically, was found to be correlated with phases of the NAO, being twice as likely to occur during the positive NAO phase compared to the negative one. The majority of patterns, however, occur on non-NAO months (either positive or negative). This is understandable, as the NAO is only one of several mechanisms which can trigger the CTP.

This connection is in agreement with previous studies dealing with quasi-stationary wavepackets and the NAO. Wolf et al. (2018) found a strong correlation between negative seasonal NAO values and decreased wave activity in the midlatitudes. Additionally, RWPs reminiscent of the preferred AS pattern can be found in Watanabe (2004), where they are identified as an Asian extension lagging positive NAO events. It is therefore possible that, within the AS group, some common trend for NAO variability (like a general shift towards its positive phase) forces this regional CTP pattern. This hypothesis is beyond the scope of this study.

Another possible explanation, which is yet to be supported by data, lies in the amplification of asymmetric diabatic forcing in the tropics. Areas of more frequent convection might excite more RWPs near a certain longitude, narrowing the overall phase distribution. Lagged regression analysis did not bolster this hypothesis, but rather showed a somewhat surprising lack of correlation.

This can be interpreted in two ways: On the one hand, a lack of evidence does not irrefutably disprove causality. The CTP is only one mode of many which influence wintertime variability in the midlatitudes. There is difficulty in singling out the CTP signal in the context of a GCM, and it's difficult to isolate its underlying mechanisms in the context of fully coupled models. Combined with the noisiness of convective proxies such as OLR, it might be that the correlation went unnoticed. On the other hand, the CTP is deeply intrinsic to midlatitude dynamics, and can most definitely indeed occur in the absence of forcing (Teng and Branstator, 2017). This means that diabatic heating might play a minor role in creating the differences in wave phasing in the models.

These hypotheses require a deeper and more theoretical analysis in the future, focusing on important unanswered questions: Are local jet stream configurations driving CTP phase preferences, and what is the mechanism behind this link? Is there a trend in NAO variability that can explain the Euroasian CTP trend? What part does tropical forcing play in this, if any? And finally, how does the ensemble spread in circulation manifest in projected surface weather and extreme events?

In order to better understand the trilateral relationship between forcing, jet regimes and wave behavior, further investigation should be performed in an idealized experimental settings. This will allow a more careful analysis of fields such as Rossby Wave Source and upper tropospheric PV. The stationary wave model used in Simpson et al. (2016) is an example of such an approach. It should be interesting to see if the model can recreate different meridional flows when prescribed different asymmetric zonal basic states based on our NA and AS group composites. Additionally, more sophisticated filtering can be applied (by wavenumber and/or through objective tracking algorithms), at the expense of generality and simplicity.

Data availability. CMIP5 Historical, RCP8.5 and Pre-industrial Control simulations used in this study are available from the Earth System Grid Federation (ESGF).

Author contributions. DS led the data analysis and writing of this manuscript. NH supervised the project, and aided with designing the calculations, interpreting the results, and writing the manuscript.

Competing interests. The authors declare that they have no competing interests.

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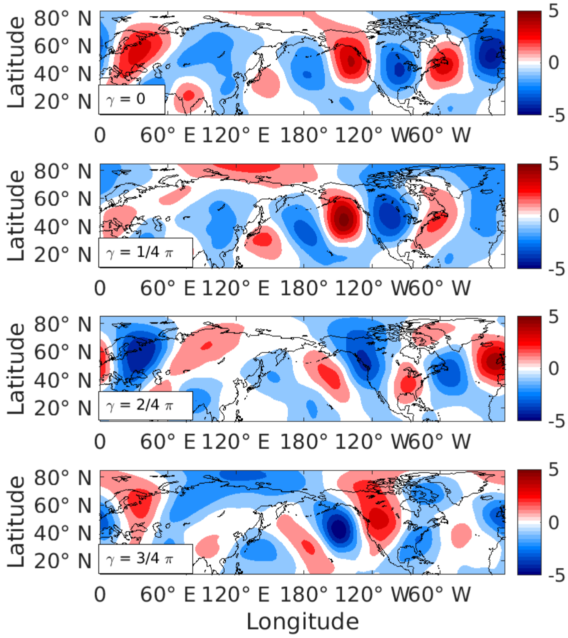


Figure 1. A simplified example of the relation between EOF phase angle and longitudinal phase. Each plot consists of a combination of the first two leading observational EOFs (represented by the γ value in Eq. 1). Red (blue) shading denotes positive (negative) V values.

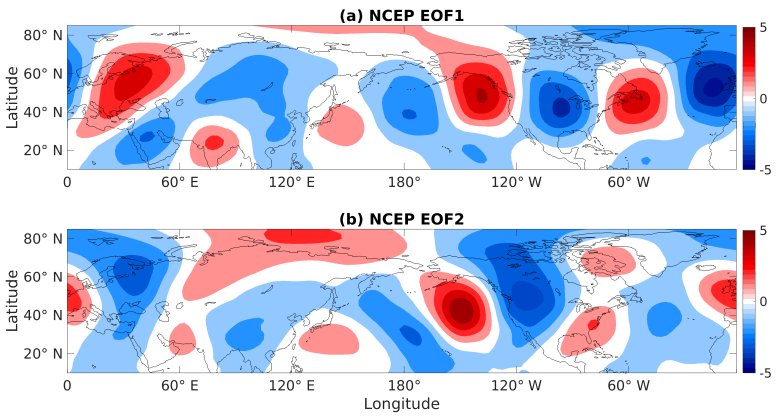


Figure 2. The first two empirical orthogonal functions (EOFs) of NCEP/NCAR monthly mean seasonal anomalies of 300 hPa DJF meridional wind. Red shading is positive and blue is negative here and throughout, with intervals of 1 ms^{-1}.

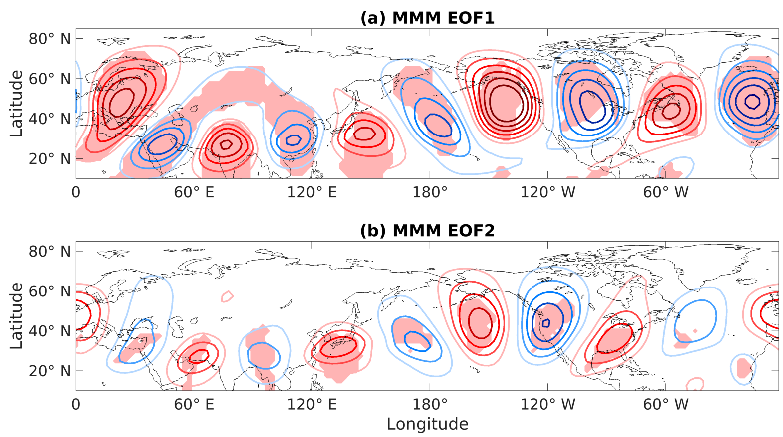


Figure 3. Multi-model mean EOFs for monthly mean seasonal anomalies of 300 hPa DJF meridional wind, based on Historical runs of 36 GCMs. Contour interval is 0.5 ms^{-1} and shading represents areas where >90 % of models agree with the sign of the observational EOFs.

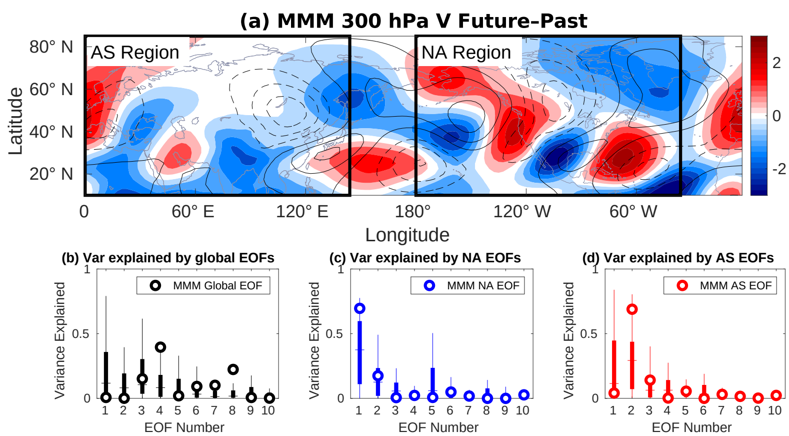


Figure 4. a) Multi-model mean 300 hPa DJF meridional wind. Contours show Past (1979-2005) climatology, and shading denotes the anomaly between Future period (2070-2099) and Past(1979-2005). ; Boxed regions are the domains used for regional EOF calculations and projections hereafter (AS - Euroasia; NA - Pacific North America). Contour interval is 0.5 3 ms^{-1} and the zero contour is omitted; b-d) Percentage of spatial variance of every model's anomaly (similar to the shading in a), as explained by its leading ten global (b) and regional (c,d) EOFs. Horizontal lines are the ensemble median, bold vertical bars cover the interquartile range, and thin bars mark the top and bottom quartiles. White circles denote the results for the same calculation, performed with the MMM EOFs and anomaly.

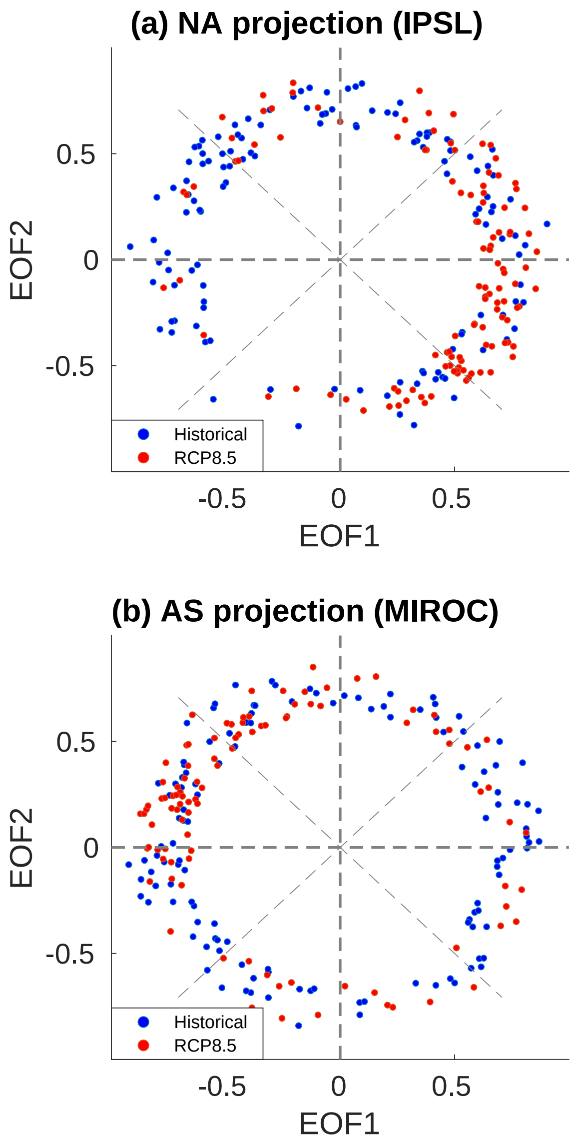


Figure 5. Examples of the monthly phase space. Projection of 300 hPa monthly DJF V anomalies onto regional EOFs in two ensemble members: IPSL-CM5A-MR in the NA region (a), and MIROC-ESM-CHEM in the AS region (b). Blue (red) dots are Historical 1900-2005 (RCP8.5 2006-2099) monthly deviations from a 1900-1930 climatology. For clarity, only strongly projected months were included.

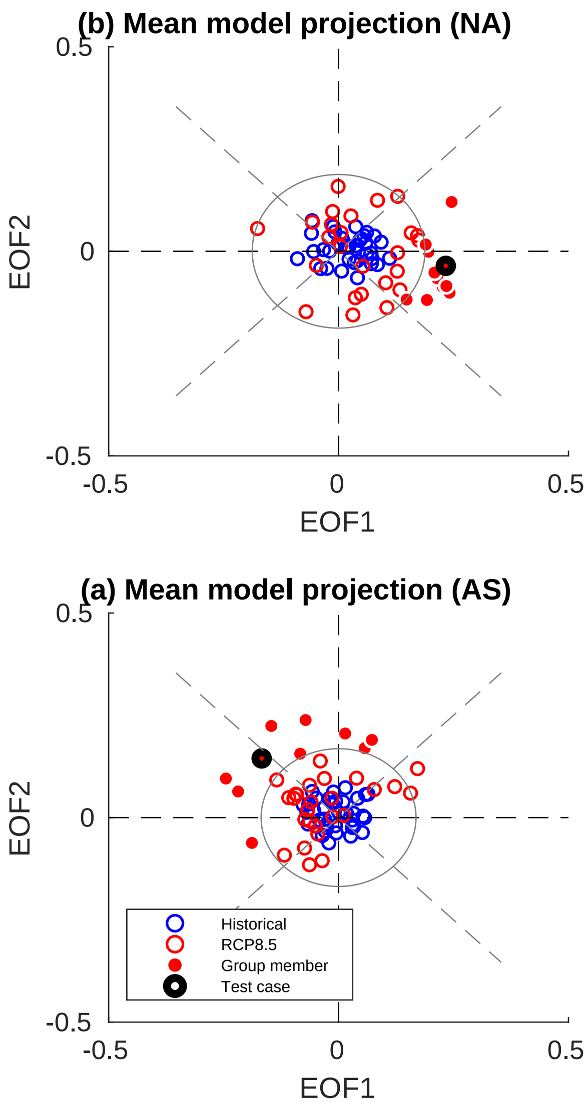


Figure 6. Mean location of every model on the (a) EOF_{NA} and (b) EOF_{AS} phase space. Each blue (red) marker represents the mean projection score of all Historical (RCP8.5) DJF months. Filled ~~squares~~ circles are models that were classified to the preferably-phased groups, with a score bigger than 1σ (denoted by the ~~black~~ grey circle). Highlighted markers show the two GCMs chosen as test cases for daily data projections.

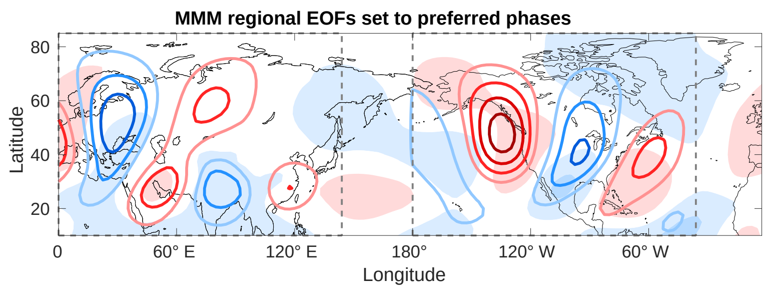


Figure 7. Linear combination of regional EOFs. In contours: $\cos(\gamma)V_{EOF1} + \sin(\gamma)V_{EOF2}$. γ is set to represent each group's approximate preferred phasing ($-\pi/8$ for NA, $3\pi/4$ for AS). Contour interval is 1 ms^{-1}. Light shading is the MMM Future-Past V trend, and dashed lines define the domains of the regional EOFs.

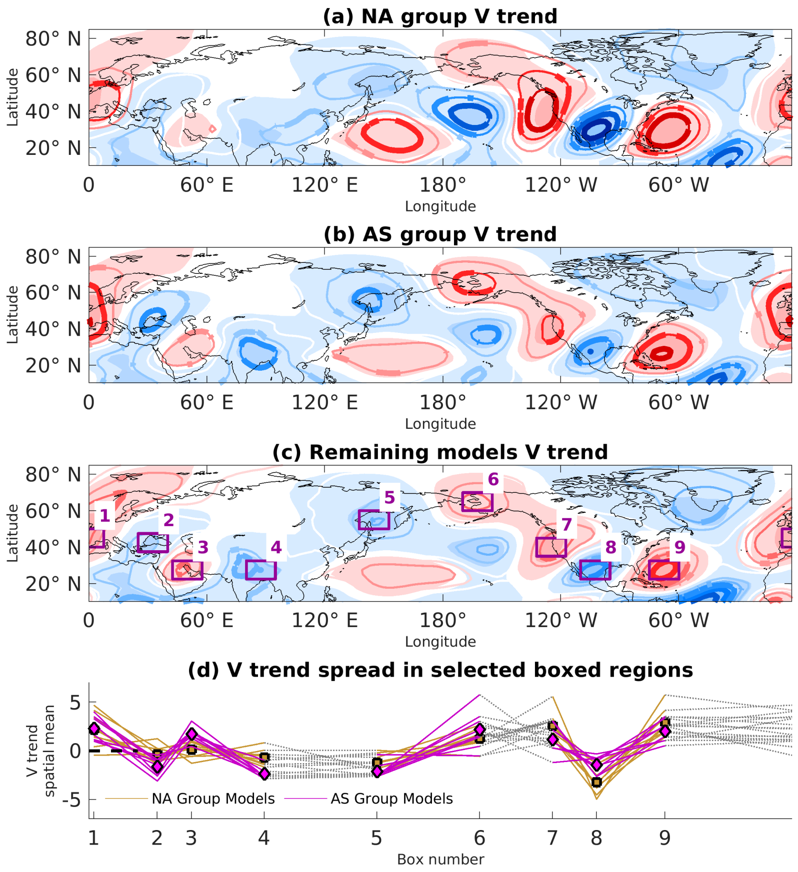


Figure 8. The Future-Past 300 hPa DJF V climate trend for all models in the NA (a), AS (b) and NONE groups (9, 8 and 17 models, respectively). The two models with preferred phasing in both regions (BOTH group) were added to the (a) and (b) composites. Contour interval is 1 ms^{-1}, and the bold contours signify areas where over 90 % of group members share the same sign with the composite. In shading, the MMM V trend as in Figure 4a. d) shows the spatially averaged V trend (ms^{-1}) in the nine boxed regions in (c), for every model in the NA and AS groups (orange and magenta, respectively). Square (diamond) markers denote the NA (AS) group mean for every box. Some lines are partially grayed out to better indicate separate geographical regions.

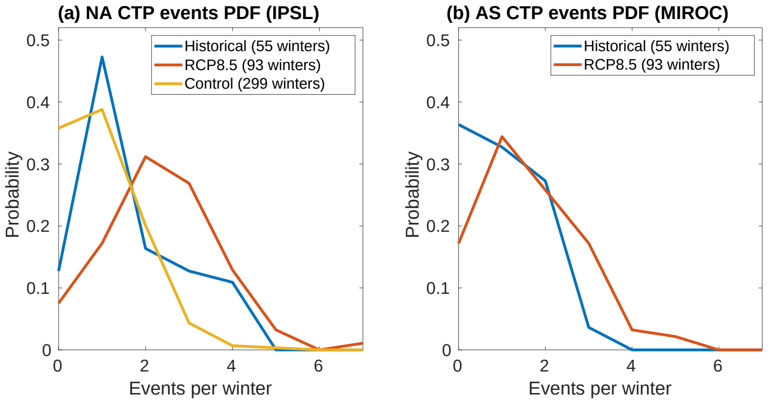


Figure 9. Histograms of the probability of CTP event frequency per winter, for (a) IPSL-CM5A-MR and the NA region and (b) MIROC-ESM-CHEM and the AS region. The blue, red and yellow lines signify the Historical (1950-2005), RCP8.5 (2005-2099), and Pre-industrial Control (1800-2099) runs, respectively.

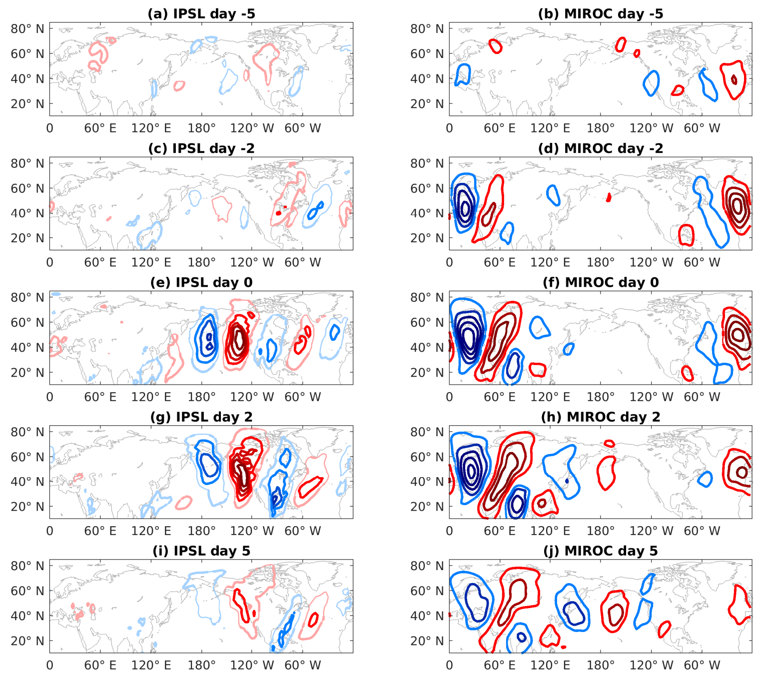


Figure 10. Lag composite of CTP events for days -5, -2, 0, 2 and 5. The composites are comprised of 500 hPa daily V deviations from RCP8.5 mean (2006-2099), for IPSL-CM5A-MR (a,c,e,g,i) and MIROC-ESM-CHEM (b,d,f,h,j). The IPSL (MIROC) composite consists of 222 (165) events. Contour interval is 1 ms^{-1} for the IPSL plots, and 2 ms^{-1} for the MIROC plots. Thick contours mark 95 % statistical confidence under a bootstrap two-tail t-test.

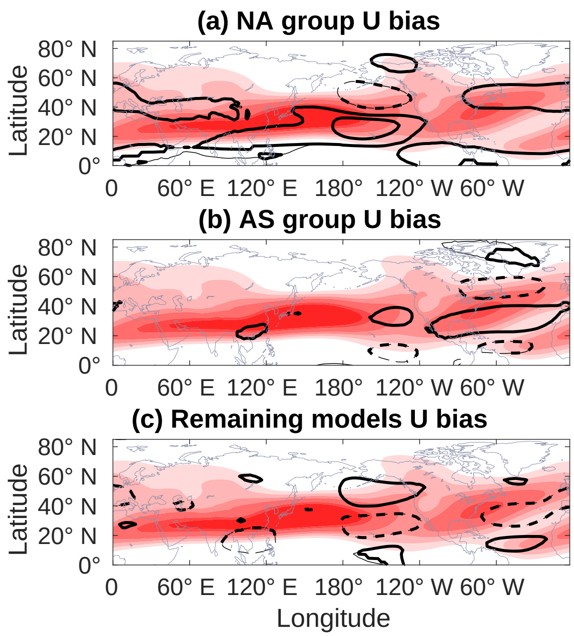


Figure 11. Group bias in the jet stream. Data shown is monthly 300 hPa DJF zonal wind group composites for the Past period (1970-2005), with the MMM pattern removed. Contour interval is 1 ms^{-1}, with negative values denoted by dashed lines. Thick contours show areas where at least 90 % of group members have the same sign as the group mean. Shading represents the MMM 300 hPa climatological jet stream ~~($U \geq 20ms^{-1}$),~~ averaged over the same period ($U \geq 10\ ms^{-1}$, shading interval is 5 ms^{-1}).

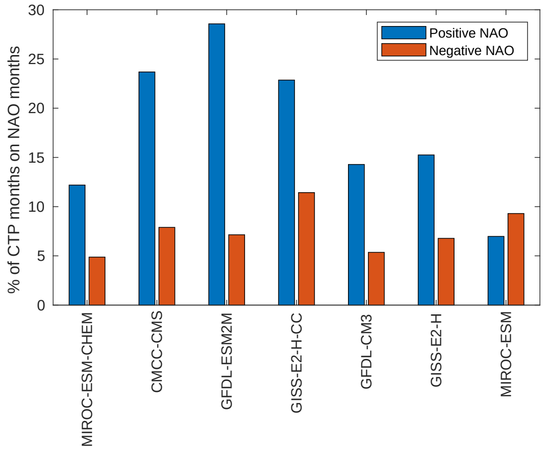


Figure 12. Share of preferably phased RCP8.5 CTP months in the AS domain, that occur concurrently with a positive (blue) or negative (red) NAO phase. All models shown are from the AS group.

Table 1. CMIP5 model groups based on preferred regional CTP phasing of monthly mean data projection.

NA Group	AS Group	BOTH Group	NONE Group	
bcc-csm1-1	CMCC-CMS	IPSL-CM5A-LR	ACCESS1-0	GISS-E2-R-CC
bcc-csm1-1-m	GFDL-CM3	CSIRO-Mk3-6-0	ACCESS1-3	HadGEM2-CC
CESM1-BGC	GFDL-ESM2M		CCSM4	HadGEM2-ES
CMCC-CESM	GISS-E2-H		CESM1-CAM5	MIROC5
CMCC-CM	GISS-E2-H-CC		CESM1-WACCM	MPI-ESM-LR
HadGEM2-AO	MIROC-ESM		CNRM-CM5	MPI-ESM-MR
inmcm4	MIROC-ESM-CHEM		FGOALS-g2	MRI-CGCM3
IPSL-CM5A-MR	NorESM1-ME		FIO-ESM	NorESM1-M
IPSL-CM5B-LR			GFDL-ESM2G	

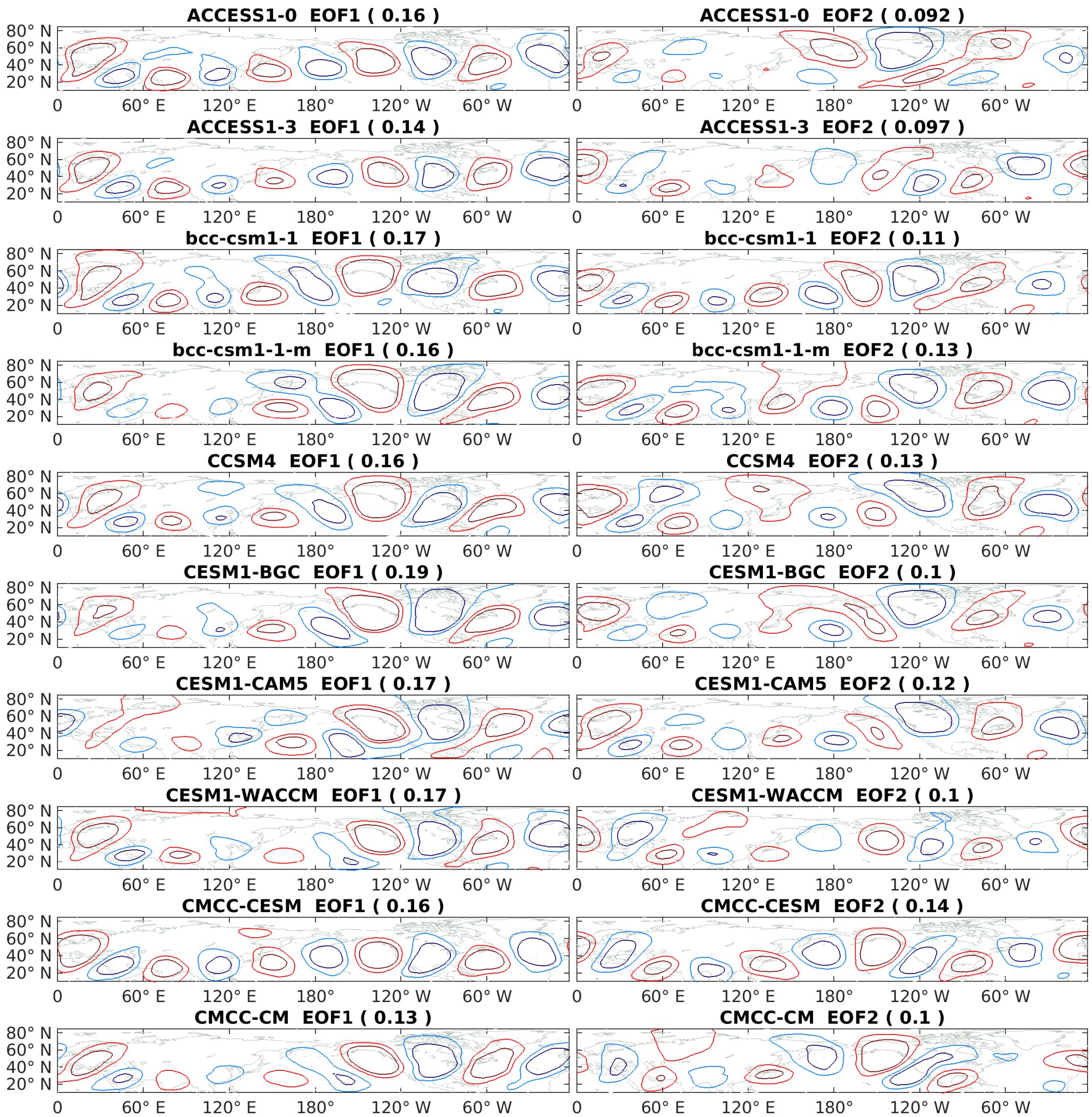
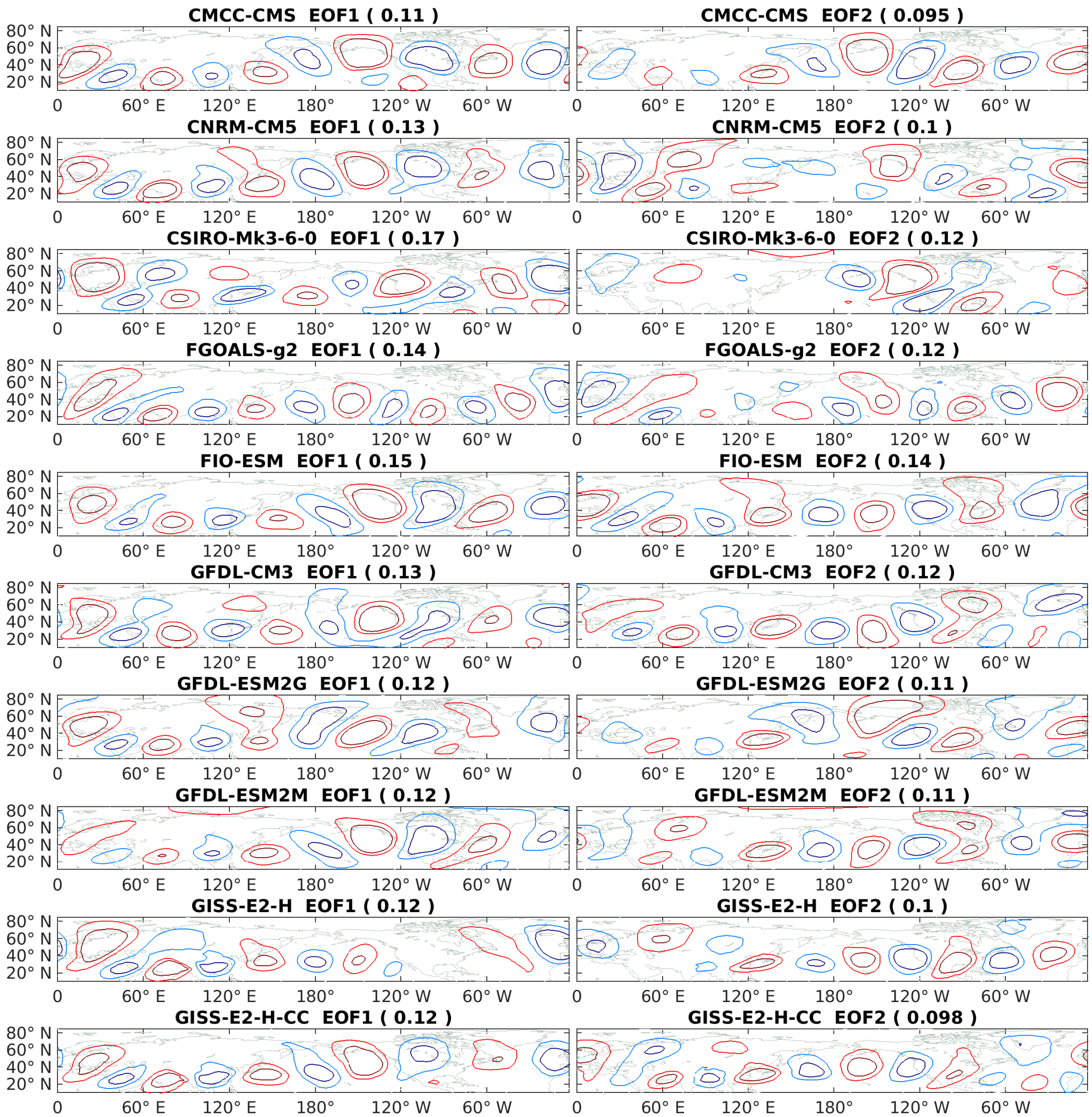


Figure S1. Individual CMIP5 models' first two leading V EOFs, based on Historical DJF data - 300hPa monthly subseasonal anomalies for the entire NH. The λ value for each EOF is denoted in parentheses in the titles. Positive (negative) values are displayed in red (blue), with an interval of 1 ms^{-1}. Contours greater than 2 ms^{-1} were omitted for clarity.



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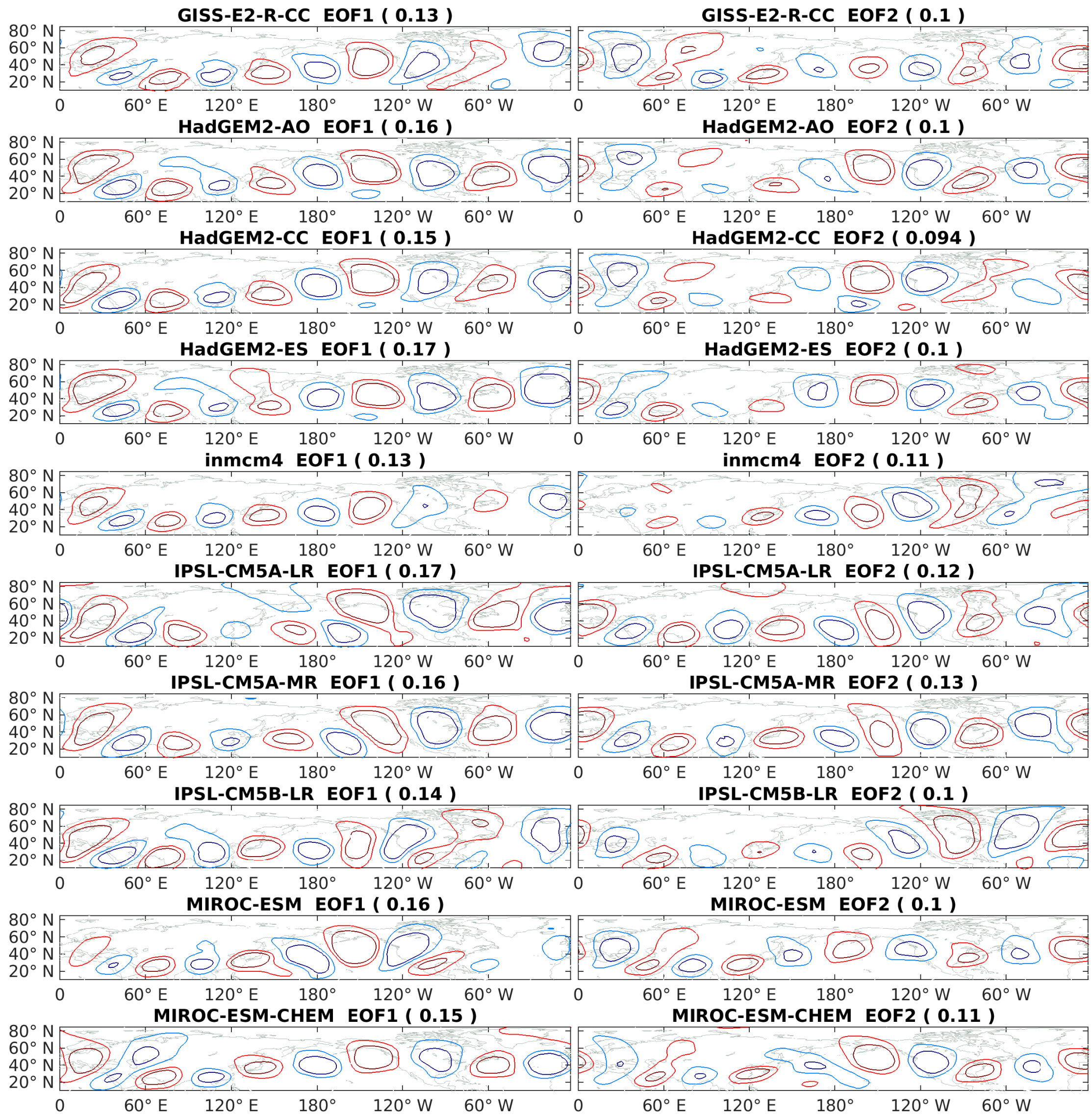

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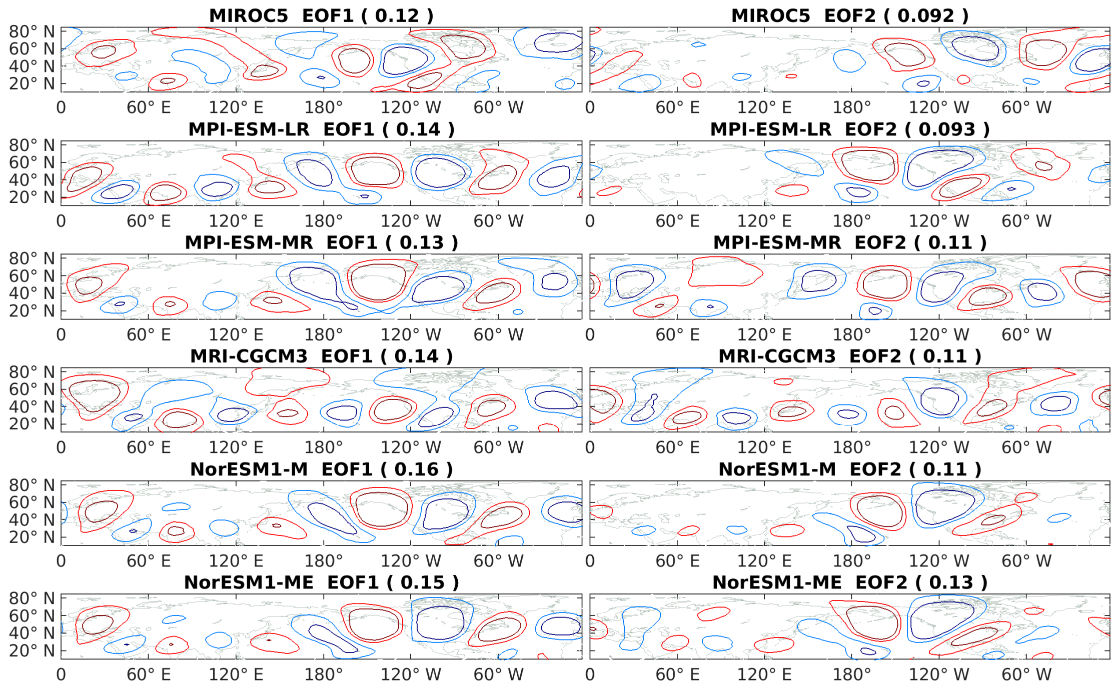

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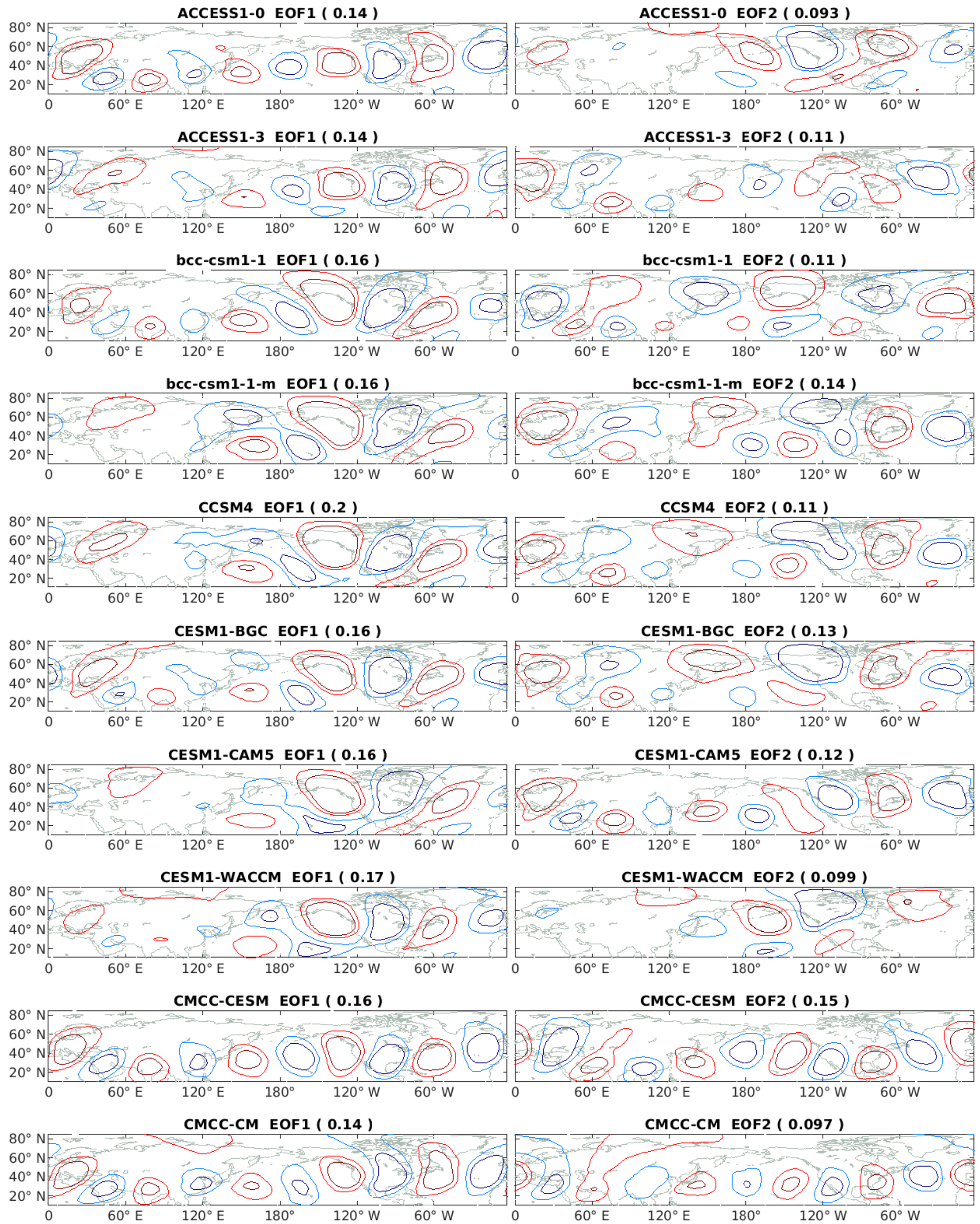


Figure S2. The first two leading Historical MMM V EOFsSame as Fig. S1, calculated but for the entire NH (shading) and for the NA and AS sectors (contours)EOFs calculated with RCP8.5 runs.

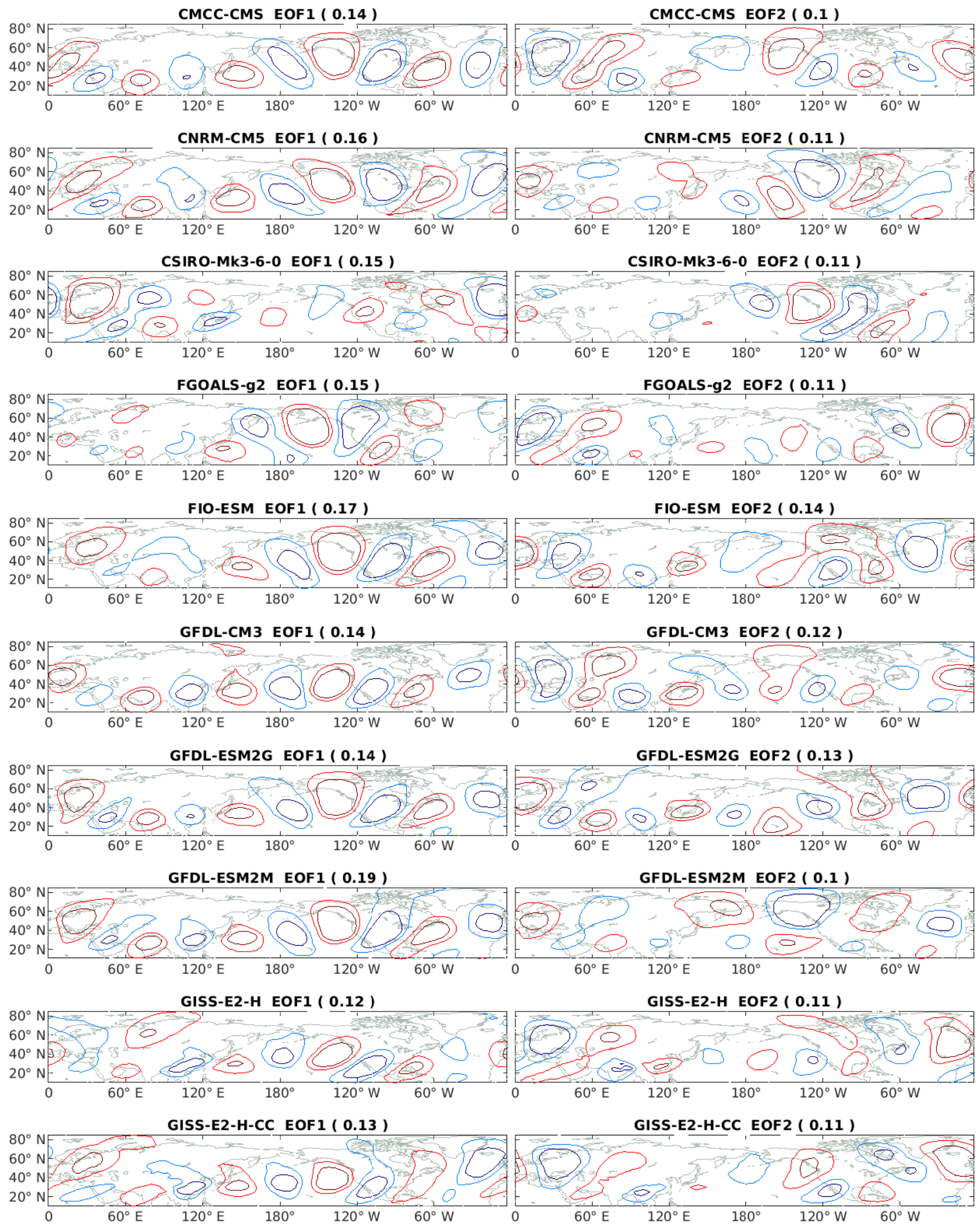


Figure S2. Same as Fig. S1, but for EOFs calculated with RCP8.5 runs.

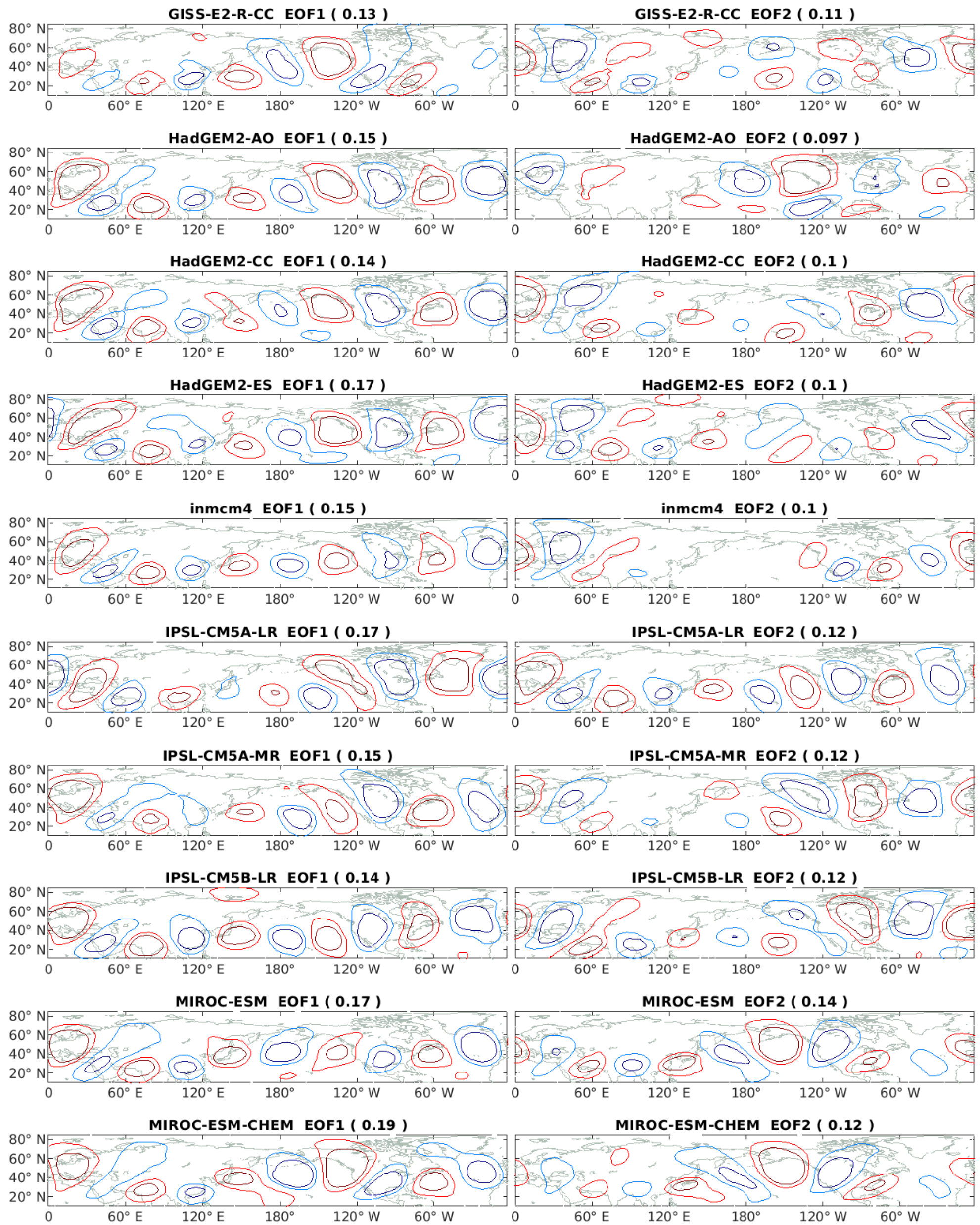
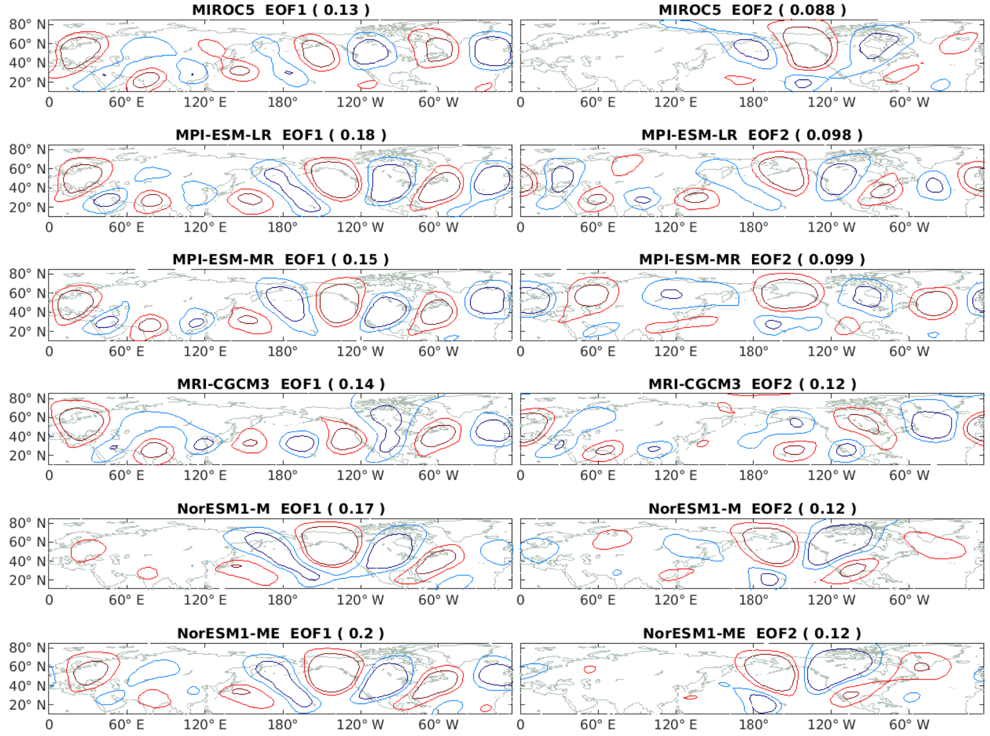


Figure S2. Same as Fig. S1, but for EOFs calculated with RCP8.5 runs.



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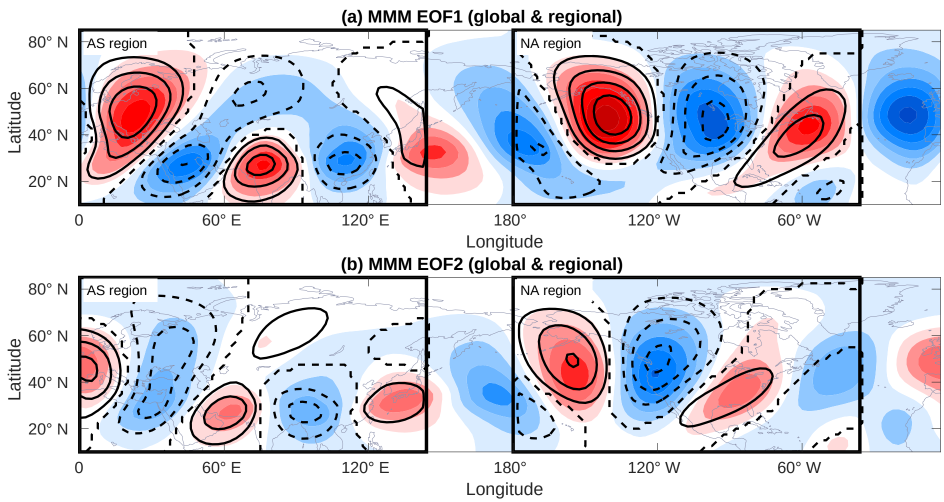

Figure S3. The first two leading Historical MMM V EOFs, calculated for the entire NH (shading) and for the NA and AS sectors (contours).

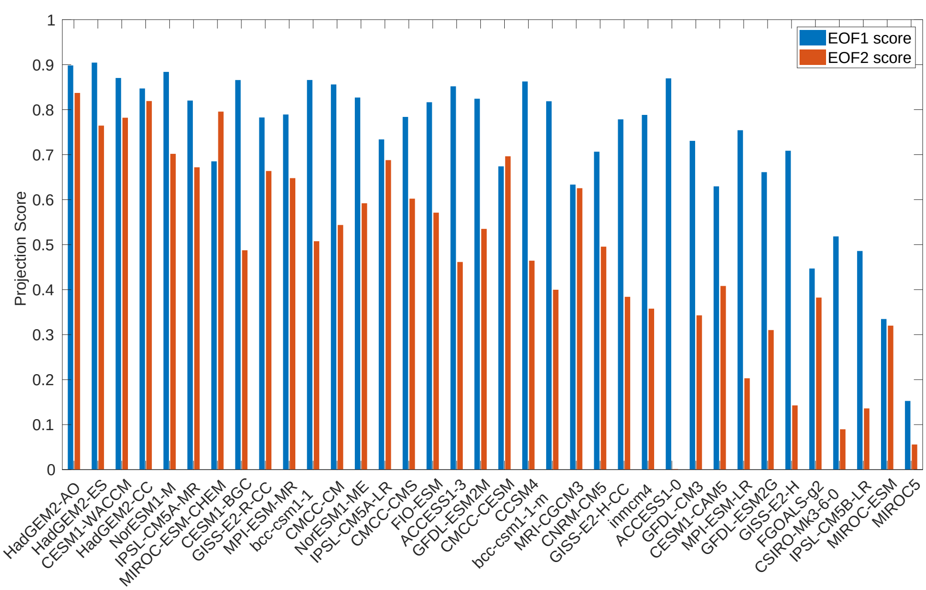

Figure S4. Model skill for EOF representation, as expressed by the Pearson correlation coefficient between the cosine latitude weighted global functions and the NCEP-I patterns.

S1 Definition and filtering of CTP Events

We define "CTP events" in daily mean data. These are essentially Rossby Wave Packets which are nearly in phase with the 500 hPa equivalent of the preferably-phased pattern that was found in the 300 hPa monthly projections. First, we apply a 3-day running mean on the 500 hPa daily V field. After calculating the projection index and excluding low values (as in the monthly case), we detect all sequences of 3 or more consecutive daily timesteps in which $|\gamma_d - \gamma_m| \leq \pi/8$, where γ_d and γ_m are the daily and preferred-monthly phases respectively. Lag 0 of a CTP event is defined as the first day of the sequence. Two consecutive sequences that are not separated by at least 48 hours are considered one CTP event. Our results were not found to be sensitive to the choice of these parameters. This method of filtering results in some false positive matches. We therefore further filter out all sequences whose composite does not display a wavy signature (alternating mean negative-positive-negative anomalies in the boxes marked in Fig. 8c). In order to determine the statistical significance of the resulting event composites, we use a 1000 member bootstrap method.

S2 Lagged linear regression of tropical proxies

We used lagged linear regression in an attempt to establish a causal relationship between tropical convective forcing (expressed by OLR and upper tropospheric divergence) and the excitation of CTP events. After choosing a base daily time series as an independent variable (X_i), we regress onto it the 7-day lagged time series of a chosen dependent field (Y_i). Multiple regression equations are then derived, one for every gridpoint of Y. We map the resulting Y pattern by plugging an identical arbitrary x value in every equation. Statistical significance is assessed through the p-value of the correlation coefficient.

Following Livezey and Chen (1983), we assume that the coefficient's distribution is normal with a standard deviation of $1/\sqrt{n-3}$. n is the number of degrees of freedom, estimated by:

$$n = N/[1 + 2\sum_{i=1}^{N} C_{XX}(i\Delta t)C_{YY}(i\Delta t)]$$

Where N is the number of samples, Δt is the sampling time (1 day) and $C_{ZZ}(i\Delta t)$ is the autocorrelation of Z for lag $i\Delta t$.

Table S1. CMIP5 models used in this study. All data was taken from monthly-resolution Historical and RCP8.5 runs. Models denoted by (*) were studied as test cases using daily data.

Model Name	Institution
ACCESS1.0 ACCESS1.3	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology
BCC-CSM1.1 BCC-CSM1.1(m)	Beijing Climate Center, China Meteorological Administration
CCSM4	National Center for Atmospheric Research, United States
CESM1(BGC) CESM1(CAM5) CESM1(WACCM)	National Center for Atmospheric Research, United States; Community Earth System Model Contributors
CMCC-CESM CMCC-CM CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici
CNRM-CM5	Centre National de Recherches Météorologiques / Centre Européen de Recherche et Formation Avancée en Calcul Scientifique
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence
FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences and CESS, Tsinghua University
FIO-ESM	The First Institute of Oceanography, SOA, China
GFDL-CM3 GFDL-ESM2G GFDL-ESM2M	NOAA Geophysical Fluid Dynamics Laboratory, United States
GISS-E2-H GISS-E2-H-CC GISS-E2-R-CC	NASA Goddard Institute for Space Studies, United States
HadGEM2-AO	National Institute of Meteorological Research / Korea Meteorological Administration
HadGEM2-CC HadGEM2-ES	Met Office Hadley Centre, United Kingdom
INM-CM4	Institute for Numerical Mathematics, Russia
IPSL-CM5A-LR IPSL-CM5A-MR(*) IPSL-CM5B-LR	Institut Pierre-Simon Laplace, France
MIROC-ESM MIROC-ESM-CHEM(*) MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute and National Institute for Environmental Studies
MPI-ESM-MR MPI-ESM-LR	Max Planck Institute for Meteorology, Germany
MRI-CGCM3	Meteorological Research Institute, Japan
NorESM1-M NorESM1-ME	Norwegian Climate Centre