Reviewer 2

This study investigates the characteristics of the extreme meridional energy transport associated with various zonal scales, using the reanalysis data. Using Extreme Value Theory, extreme events of the meridional energy transports are identified, and their associated zonal wavenumbers and meteorological patterns are analyzed. They found that extreme energy transports are, in general, associated with planetary (synoptic) scale wave during boreal winter (summer). Further, they connect those extreme energy transport events with commonly known teleconnection patterns. The topic and the results of this paper generally fits the aim of the WCD and would improve the scientific community's knowledge about the meridional energy transport.

However, I found that the manuscript's writing and the scientific results are vague. I think the Introduction needs more strong motivation and hypothesis, and the Methodology section should be written with more details as readers with meteorological background might not be familiar with advanced statistical method such as EVT. More importantly, I found it very difficult to digest the meteorological and dynamical interpretations of the extreme events presented in the Result and Discussion sections. My specific comments are presented below.

We wish to thank the reviewer for the timely and accurate revision, for the constructive criticisms that have inspired fruitful discussions on how to improve the conveyance of the main message and better placement in the context of current research on the role of extremes and energy exchanges in a changing climate. Replies to specific comments are marked below in red, illustrating the changes that will be proposed in a revised version of the manuscript.

Introduction

First three paragraphs introduce general information of the meridional energy transport, and L48-51 only mentions the plan of this paper. Yet, I think the introduction can be improved by adding more motivations and hypothesis. Here are some suggestions.

- Why do we need to pay attention to the energy transport extremes at different length scales? I think L33-35 touches this issue, but it is not so clear to me how planetary waves can oppose the total transport. I think it just depends on the structure and the phase of the wave itself, and thus one cannot make a general statement about it. Can you provide some more references or more explanations?

A substantial body of literature is pointing towards the role of meridional energy transports in communicating the climate change signal towards the high latitudes, especially when one takes into account the latent energy part of the moist static energy (Hwang et al. 2011, Skific and Francis, 2013). More recently, it has been found that transient eddies are mostly responsible for the convergence of atmospheric latent energy towards the high latitudes (Boisvert and Stroeve, 2015). The intermittent and sporadic nature of eddy-driven meridional energy transports, as discussed in Woods et al. 2013, Messori et al. 2013; Messori et al. 2015, justifies the importance of detecting, and characterizing in terms of dynamical mechanisms, extreme meridional energy transport events, as they can contribute substantially to the warming of the Arctic (e.g. Rydsaa et al., 2021). A wavenumber, rather than the traditional stationary-transient (Peixoto and Oort, 1992) decomposition, allows an in-depth consideration of such dynamical aspects. For instance, Graversen and Burtu 2016 found that the planetary scales were themselves mostly responsible for the temperature warming in the Arctic caused by latent energy convergence. Recent works, using the Fourier decomposition introduced in Graversen and Burtu, 2016 or similar methods (cfr. Heiskaanen et al. 2020), found that planetary scales in atmospheric energy transports are substantially important for the Arctic amplification, unlike synoptic scales, and that their contribution has significantly increased in the last decades (cfr. Rydsaa et al. 2021). Despite the work looking into extreme events in order to understand Arctic changes, and hinting at the role of weather systems (e.g. Liu and Barnes 2015) and storm tracks (Dufour et al. 2016), to our best knowledge no effort has been made yet to link dynamical configurations of the atmosphere to extremes in the meridional energy transports. This is the scope of our analysis and we will rearrange the Introduction accordingly, accounting to the brief excursus that has been summarized above.

Regarding the peculiarity of planetary-scale transports, sometimes opposing the total transports, we believe that the sentence at ll. 33-35 has to be rephrased, as it may wrongly suggest that the planetary-scale transport is not a component of the overall total transport. What we aimed at observing here, was that the contribution of planetary scales to the overall transport, especially in the weak JJA transports, as found in Lembo et al. 2019, can transport energy equatorward, rather than poleward, in this way opposing the sign of the total transport. This is a signature of a counter-gradient eddy transport, that goes against the usual baroclinic conversion observed in mid-latitudes, and points towards a different mechanism that is yet to be understood. Understanding the role of planetary scales, as also pointed out in Rydsaa et al. 2021, is increasingly relevant in a warming climate, with ongoing debate on whether the decreasing meridional temperature gradient by Arctic amplification is setting more favorable conditions for the propagation and growth of planetary-scale waves (cfr. Barnes and Polvani 2013; Fabiano et al. 2021; Moon et al. 2022).

- What is the main hypothesis? What do authors expect to find out by analyzing the different component of the meridional transport, for different seasons?

Regarding the main hypothesis of this work, see our comment above. Regarding the relevance of breaking down the meridional transports and their components to different seasons, on one hand it has been found that the role of atmospheric energy transport is particularly relevant in winter, on the other hand not as much interest has been put into the development of waves and the strength of the meridional heat transports in summer. We already found in Lembo et al. 2019 that the relative contribution of synoptic and planetary scales radically changes in the two seasons, especially because of the planetary scales. In this work, it is our intention to develop further such ideas, retaining the focus on extreme events during the two seasons.

Method:

- L92: Authors have defined the planetary scale to be k=1 to 5, while some previous researches have defined waves with zonal wave number 1 to 3 as planetary scale waves and wavenumber 4 or higher as synoptic scale waves (cf. Baggett and Lee 2015; Shaw 2014 https://doi.org/10.1175/JAS-D-13-0137.1). Therefore, some discussion to justify the author's choice of the threshold between planetary and synoptic scale wave number would be helpful. Also, in L276, authors refer k=5 as a synoptic scale wave which is not consistent with the definition of the synoptic scale used in this paper.

Correct. We will change l. 276 accordingly.
As for the choice of the wavenumber ranges, we acknowledge that the choice of the threshold for the separation between planetary and synoptic scales is somehow arbitrary and deserves some more

justification, that will be provided in Section 2.2.1. We hereby note that our approach basically follows the one of Graversen and Burtu, 2016 (and subsequently Lembo et al. 2019). The threshold results by the consideration that different length scales correspond to the same wavenumber at different latitudes (as discussed in Heiskanen et al. 2020), our choice being consistent with lower threshold (k=3 for Rydsaa et al. 2021, k=4 for Shaw et al. 2014) at higher latitudes. We argue that the choice of the wavenumber groupings does not substantially affect the interpretation of our results.

Nevertheless, Figure R1 shows what a different grouping, for instance consistent with Rydsaa et al. 2021 would imply for our interpretation of the extreme events. The different grouping consists here of the zonal wavenumbers, k=1-3, that can be denoted as "ultra-long planetary waves", k=4-6, as "planetary waves", k=7-9 as "synoptic waves''. The panel k=0, i.e. zonal mean, is left unchanged. Starting from the DJF season (left panel), it is confirmed that ultra-long planetary waves are dominant, especially in the definition of "poleward" extremes at higher latitudes, whereas other planetary waves are relevant at all latitudes (with homogeneous contribution across latitudes). The contribution of synoptic waves is weaker, although comparable to planetary waves, especially in the equatorward half of the mid-latitudinal channel. Looking at JJA, the three eddy contributions are comparable, with planetary and synoptic waves mostly contributing to poleward extremes in the middle of the channel, and ultra-long planetary waves contributing at lower and higher latitudes. Interestingly, ultra-long and planetary waves have a significant part of their PDFs related to equatorward extremes in the negative domain. In other words, we claim that both components transport energy "counter-gradient", as opposed to the total transport.

Overall, one might notice that:

- synoptic-scale waves defined in this way are remarkably homogeneous in latitudes and constant across seasons, so that the only appreciable change is in the position of the peak. This is somehow coherent with our approach, considering k=6-10 as the synoptic wave domain;
- ultra-long planetary waves play a dominant role in shaping the extremes in the DJF season, and this is consistent with the "fine tuning" of the spectrum that we perform at Figures 7 and 8. Not differently, JJA extremes are characterized by the coexistence of comparable planetary and synoptic contributions, although the former ones still dominate poleward transports, while ultra-long waves hardly distinguish between poleward and equatorward extremes;
- the regrouping of wavenumbers allows us to observe that the strength of the extremes is in all cases dependent on the shape of the median meridional section. The k=1-5 grouping showing non correlation with the median, is the result of the latitudinally homogeneous median in the k=4-6 range, plus the weaker contribution by ultra-long waves in low latitudes;

We will consider including these arguments in a dedicated Appendix.

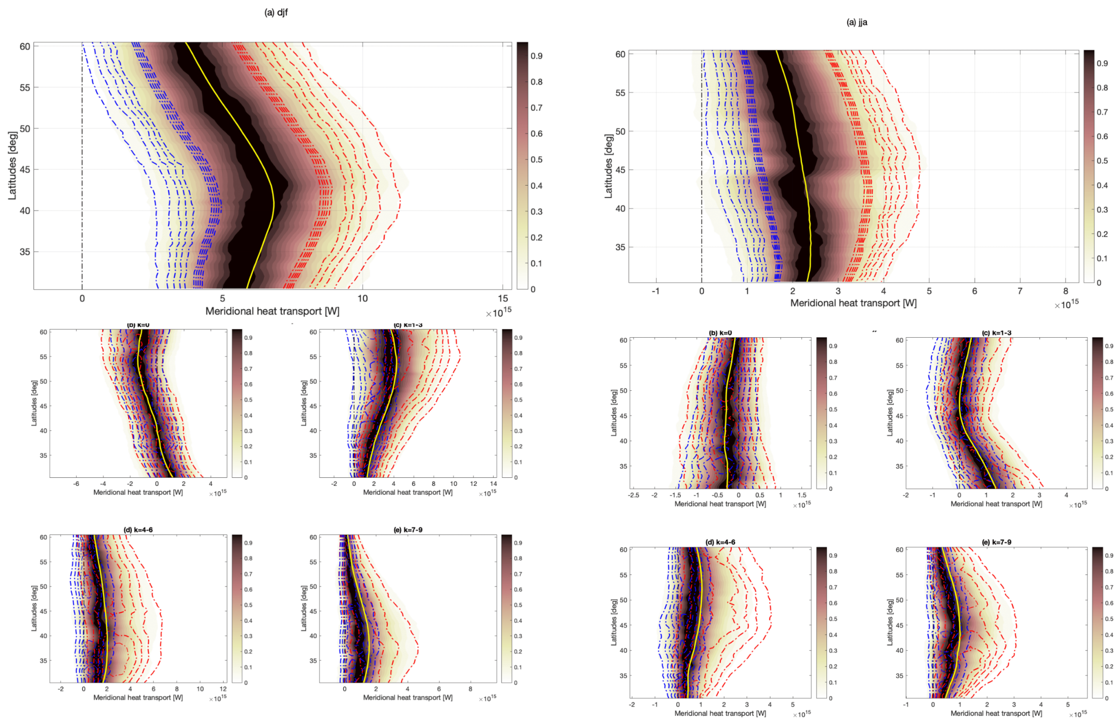


Figure R1: PDFs of total (filled contours) and extreme poleward (red contours) and equatorward (blue contours) DJF (left) and JJA (right) meridional energy transports over the 1979-2012 period in ERA5. (a) Sum of all wavenumber contributions; (b) k=0 (zonal mean); (c) k=1-3 (ultra-long planetary scales); (d) k=4-6 (planetary scales); (e) k=7-9 (synoptic scales). Total PDFs have been normalized at each latitude; PDFs of extremes are weighted at each latitude by the number of extreme events. Yellow lines denote mean values.

- L124-126: I think this is a serious issue. If authors decided to remove the trend, then they should remove it from the entire grid point. Removing trend only at certain latitudinal band may result a physical unrealistic field and further analysis based on these data would make the readers to suspect the results. So, I suggest either do not remove the trend or remove the trend from the entire grid point. Or at least, authors should provide some information (perhaps as a supplementary figures) that qualitative results don't change regardless of the de-trending method (Even if the results may qualitatively remain same, authors would need to justify their choice anyway).

Agreed. As this was also brought up by reviewer 1, we show in Figure R2 how the thresholds look like if the trend and seasonal cycle are removed everywhere. Whereas the detrending alone (not shown) does not noticeably change the results, the deseasonalizing has a slight effect in DJF, as it can be seen in the first two rows of the figure. There is (left) a small discontinuity at latitude 45°, coinciding with the latitude north of which no deseasonalization has been originally performed. This small discontinuity disappears when the transports are deseasonalized at each latitude (right). However, the change is really minor, especially for the selected thresholds marked by the blue dots, thus it does not affect our results. In case of JJA, there is no noticeable change between the two procedures (left vs. right).

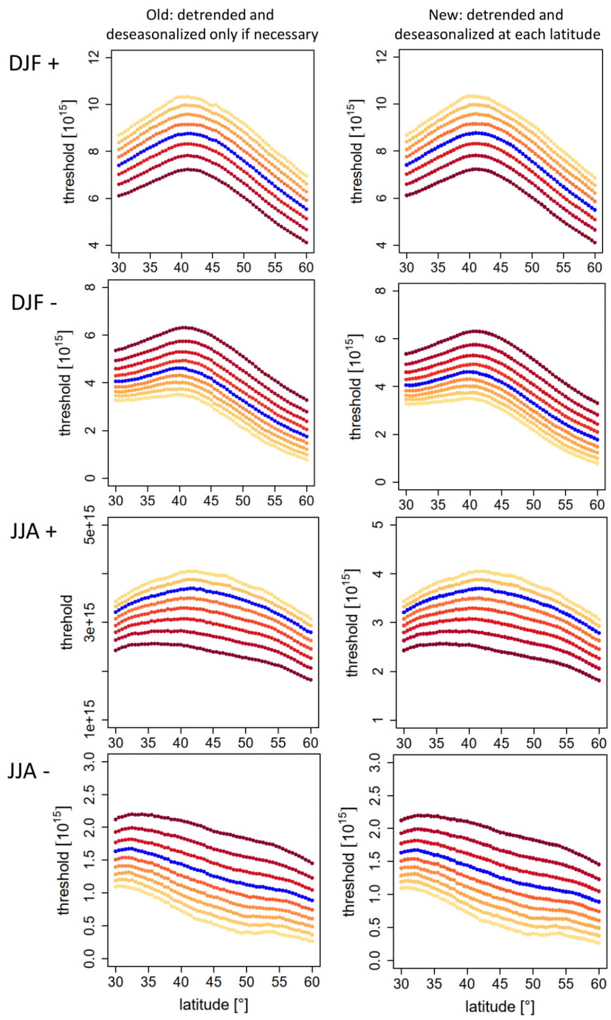


Figure R2: Meridional section of threshold values for meridional energy transport extremes selection considering different percentiles (the selected threshold is highlighted in blue, as in Figure 1 of the manuscript). In the left column, transports have been deasonalised and detrended only where necessary, in the right column everywhere: (1st row) DJF, poleward, (2nd row) DJF, equatorward, (3rd row) JJA, poleward, (4th row) JJA, equatorward.

- L150-157: Authors argue that Figure 1 justifies the choice specific threshold values. However, even after looking at Figure 1, I cannot understand how authors have chose these specific threshold value (ex: 86% percentile for DJF poleward). So more detailed explain regarding this step would be helpful.

The convergence algorithm implies that the shape parameter does not change for thresholds (i.e. percentiles) smaller or larger (depending whether we consider positive or negative extremes) than the chosen one. As the shape parameter converges in different ways at different latitudes (as shown in Figure 1 for the case of DJF "poleward" extremes) we chose by visual inspection a conservative estimate of the threshold that would account for convergence at all latitudes. We will better explain it in this part of section 2.2.2 .

- L170: Can you explain why do you first apply EOF analysis before K-means clustering? Can't you just apply K-means clustering to the raw data, or just use the PC timeseries of the first 4 EOFs?

The weather regimes analysis builds on Fabiano et al. (2020), where the details of the procedure are thoroughly discussed. The EOF decomposition is mainly aimed at reducing the dimensionality of the original field, disregarding smaller scales of motion and local noise. This is a common step in most weather regimes identification techniques (see e.g. Dawson et al. 2012, Cassou 2008, Cattiaux et al. 2013, Straus et al. 2007, Dorrington et al., 2022), although we acknowledge that some approaches skip it (Falkena et al., 2020). Sensitivity tests on the number of EOFs retained show that the regime patterns are robust to this choice (Straus et al, 2007; Fabiano et al., 2020), and the limit for very large number of EOFs clearly has to give the same result as using the full field. Clustering the higher rank EOFs would however just result in non-significant clustering, since that is mainly noise with regards to the large scale.
As for the second comment, regarding whether we could just use the PC time series for the analysis, this would represent a viable approach and is briefly addressed in Appendix B. However, we believe that weather regimes have some advantages when discussing the variability of the circulation, starting from the fact that the regimes represent persistent physical patterns that are effectively realized in the atmospheric circulation, while EOFs need to be "summed up" to reconstitute the physical field. This advantage is also reflected by the fact that weather regime analysis of the mid-latitude circulation is a very active field of research.

- I question the purpose of finding the weather regimes using a clustering algorithm. It makes more sense to me to directly diagnose the dynamical characteristics of energy transport extremes using the composite map of z500 pattern. My interpretation is that authors are hypothesizing that energy transport extremes should be associated with the identified teleconnection patterns, but that is not necessarily guaranteed. It is possible that each event may have their own circulation structure that may not resemble the known teleconnection patterns. Therefore, some discussion on why authors use clustering algorithm instead of directly diagnosing the circulation composite structures would be helpful.

We thank the reviewer for the timely comment. We agree that the composite maps of z500 patterns are helpful in analyzing the dominant pattern of the circulation related to the extremes. Indeed, we show such maps in Figures 9 and 10, which help confirming the main results of the regime analysis. However, the composites only show the mean field of all extremes, while the information on the variability is averaged out. In fact, taking the composite mean of geopotential height in the selection of extreme event dates, may result in the superposition of events occurring at different longitudes and in different times, leading to severe aliasing of the displayed anomalies. Using weather regimes gives a deeper insight on what kind of circulation patterns are linked to the energy transport extremes, since this allows to recover some information regarding the temporal/spatial variability of such extremes, which is not possible to get from the composite maps only. The significance test that we have added to Figs. 9 and 10 (see Figure R5), as suggested by the reviewer, now provides a basis to argue where and how robust the emergence of certain patterns is in composite maps, and to what extent they are consistent with the changes in the weather regimes frequency.

A concrete example of how we use the information from composite maps and weather regimes in combination is given in Figure R3. As in Figure 11a-b, we show (a) composite mean maps related to poleward extremes during JF 2010, a period characterized by a significant and persistent cold spell over large swathes of Central Asia, (b) changes in the frequency of occurrence of weather regimes and (c) dominant wavenumbers. We interpret the composite maps as a way to illustrate the mean circulation patterns during the event. It is evident from panel (b) that the regime frequencies analysis is both coherent and more detailed than the composite analysis. In other words, the anomalies associated with these extreme events are distributed in such a way that NAO+/AR, as well as PNA-/ALR, become less frequent, whereas NAO-/AO/PT occurrences are way more frequent. In this particular case, weather regimes' frequencies change in a very similar way to what happens when the overall population of extreme poleward events in all DJF seasons are taken into account (Figures 5a,c,e). Once again, we stress that a verification of the dynamical and meteorological (tele)connections leading to such occurrences of extreme meridional heat transports would require selecting a large database of events to be verified one-by-one, and this goes well beyond the scope of our work.

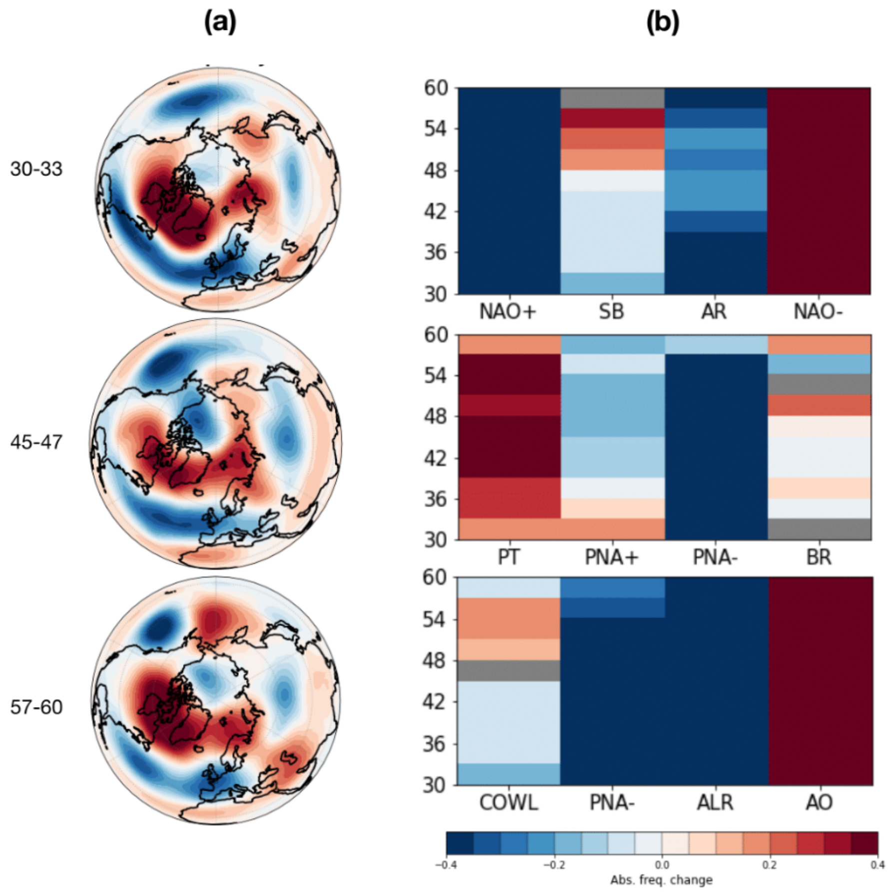


Figure R3: (a) Composite mean maps of z500 anomalies (in dam) for winter (JF) in 2010; (b) Relative variations in absolute frequency of clusters in the population of 2010's JF poleward extremes as a function of the latitude at which extremes are found, for (top) EAT region, (middle) PAC region, (bottom) NH region.

Result

- L221: If the JJA PDF shows positive skewness, are you refereeing more colored contours toward left side of the yellow (mean) line? At least to me, the difference between high and low latitude are not so clear in Figure 4a.

Indeed, we refer to panel a in Figure 4, the equatorward side of the picture. The difference in skewness is determined quantitatively, but we acknowledge that this is not stated clearly enough. We will thus rearrange the text accordingly or provide a new table including the skewness as a function of latitude.

- Can you add some scientific/meteorological interpretations of what it means to have positive skewness, and why positive skewness is an important finding?

As above, the rearranged section of the text (and possibly an auxiliary table) will contain an explanation of what a positive skewness implies. This will recall the already referenced body of literature investigating the sporadic and intermittent nature of the meridional heat transports (Ambaum and Novak, 2014; Novak et al. 2015; Messori et al. 2015; Marcheggiani et al. 2021) and its relation with the nonlinear baroclinic development of eddies in the mid-latitudes.

- L251-253: Can you explain how PT regime (Fig. 2c) can be characterized as lower latitude negative anomalies and high latitude blocking? I think this pattern is rather zonally oriented without a prominent high latitude blocking-like structure or lower latitude signals.

We agree with the reviewer that the sentence as such is unclear and wrongly suggests that the PT regime is denoted by low latitudinal negative anomalies. This was referred to AO and NAO- regimes, we will change the text accordingly. Instead, the PT regime is denoted by high latitudinal troughs and ridges in the PAC region, that are not necessarily attributable to blocking events, but determine large meridional exchanges, that are to some extent relevant for meridional heat transport extremes, as per the rationale of our work. We will better rephrase the sentence along this argument.

- It is somewhat difficult to interpret the results presented in Figs 5 and 6, along with circulation structure presented in Fig. 2. For example, JJA NHC3 is similar to winter AO, and yet they show opposite results in Figs. 5e and 6e. Besides the seasonal difference, can you comment what makes such a difference in the poleward transport even when two circulation fields are dynamically similar? In addition, EATC3 shows increasing frequency in the 30-42°N degree band (Fig. 6b), while its strong circulation patterns are rather located at higher latitude near Greenland and Scandinavia (Fig. 2b). Can you explain how this circulation pattern can be related to the equatorward transport occurring near 30-40°N latitude?

We thank the reviewer for the useful comment. When comparing weather regimes in different seasons, one has to first take into account the different amplitude of the signal. As shown in Figure 2, the scales are different, because the eddy-driven circulation is weaker in summer than in winter. This is a major constraint to make meaningful comparisons about changes in the occurrences of weather regimes over the two seasons. Even if the maps of anomalies are apparently similar, we are looking at two genuinely different aspects of the dynamics, as also hinted at by the different wavenumbers involved (cfr. Figures 3-4, Figures 7-8 and also Figure 3 in Lembo et al. 2019 for a comparison of seasonality in planetary vs. synoptic waves magnitudes seasonality). We will make this point out more clearly when defining the weather regimes for the two seasons in the Methods section.

Regarding the remote influence of equatorward extremes in JJA for some weather regimes (specifically EATC2 and EATC3), we proposed at ll. 265-266 that this could be related to the centres of baroclinic activity for these events. However, in order to establish a robust connection, an insightful investigation of baroclinic eddy activity should be carried out, so that this interpretation was left out of the main conclusions.

- L286: Authors said '...JJA and DJF differ in the fact that the higher zonal variability in the latter...'. Shouldn't this be the opposite? Figs. 7 and 8 say that JJA is associated with higher zonal variability and higher zonal wavenumber, not DJF.

This is correct, as pointed out by the other reviewer as well. We will change the text accordingly.

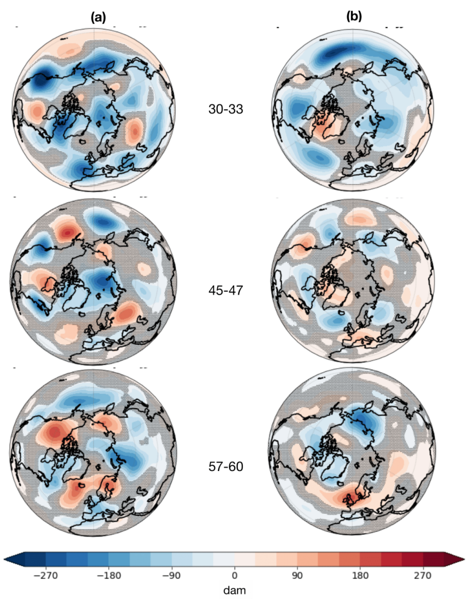
- L287-288: Authors claim that poleward extremes have more meridionally marked, or zonally uniform, structure compared to the structure of the equatorward extremes. I don't see a clear difference between poleward and equatorward (there are no (a) and (b) in Figs. 9 and 10, so I assume the poleward is the left column and the equatorward is the right column). For example, in Fig.9, both panels of the 45°N-47°N band show zonal wave number 4~5 structure without prominent meridional structure. Also, it is little unclear to me how a relatively zonally uniform circulation structure would favor for a strong meridional energy transport. I would assume meridional wind in a zonally uniform circulation to be small. Providing more detailed reasoning for such an interpretation would be very helpful.

We thank the reviewer for pointing out that the labels were missing. We have revised the figures accordingly, as shown below. Also, we agree that the claim that the meridional structure is more pronounced for poleward extremes compared to equatorward extremes is not clearly supported by the figures. We are thus planning to remove this sentence. We would rather point out that the emergence of patterns consistent with the dominant wavenumbers described in Figure 8 emerges in Figure 9a, with ridges and troughs stronger for poleward than for equatorward extremes (See Figure R5, left). Our interpretation is that it is not the uniformity of the zonal circulation that determines the strength of the transport, but rather the amplitude of the dominant waves.

- Also, Figs. 9 and 10 shows the composite mean of z500 anomalies. Please indicate the sample size of the composite, and significance test of this composite sampled is also necessary.

We will provide the additional information in the revised manuscript. As also commented below, we noticed that Figure 10 was showing incorrect maps at panels 45-47 and 57-60. We apologize for that: the correct figures are provided here.

- **Significance levels:** A bootstrapping-based significance test is performed in order to provide significance to the given maps. The 0-hypothesis that the composite mean value lies within the range of internal variability is tested at the 95-percentile. Maps are shaded where the p-value is larger than 0.05. The left panel shows results for JJA (Figure 9) and the right panel for DJF (Figure 10). The new maps shown in Figure R5 will be part of the revised manuscript.



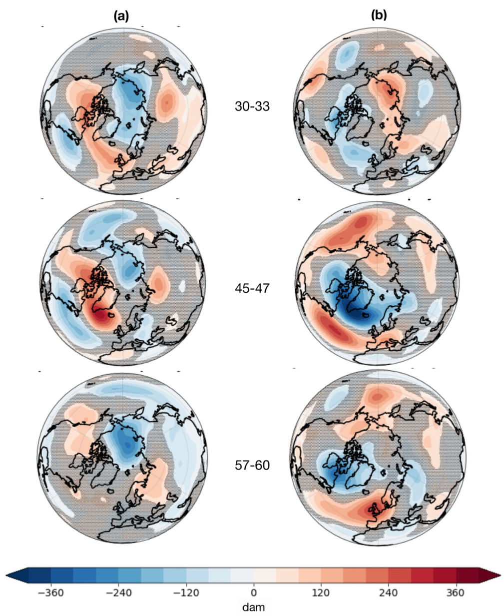


Figure R5: Composite mean of z500 anomalies (in dam) for JJA (left) and DJF (right) extremes. For each season, (a) refers to poleward extremes and (b) to equatorward extremes at 30-33 (top), 45-47 (middle), 57-60 (bottom) given latitudinal bands. The bootstrapping methodology for significance recognition is described above.

- **Size of the composites:** In the following, a small table is provided, regarding the number of samples for each extreme tail and season. We will include that in the revised version of the manuscript.

	DJF		JJA	
	poleward	equatorward	poleward	equatorward
30-33	1883	1483	1214	2237
45-47	2052	1589	1148	2260
57-60	2114	1501	1284	2452

- Regarding Figs. 9 and 10, the composite of z500 anomalies is helpful to diagnose the circulation structure, but it is yet difficult to tell where the energy transport is prominent. I think that plotting the composite of anomalous *vE* would help readers to diagnose the prime location(s) of the meridional energy transport.

We thank the reviewer for the suggestion. Our Fourier decomposition relies on the fact that zonally averaged fluxes are taken into account. This implies that we lose information on the region where the convergence and divergence of heat occurs. This is at the same time a caveat and part of the rationale behind this work. In fact, the zonally integrated view allows one to consider the problem from a budgetary point of view: in other words, since extreme meridional heat transports can take up to 55% of the energy that is transported poleward across the midlatitudes in a season (cfr. Messori et al. 2015), which wavenumbers are mostly responsible for such transports? This is one of the questions we aimed to answer with this work. We also realized that a view of the situation in terms of transport ratios allocated in the different wave groups is missing, and we aim at including it in the revised version of the manuscript.

To give a sense of what the situation is, when looking at geographical maps of meridional heat transports and why they are not informative because of the zonally integrated approach, in Figure R4 we show the composite time means of meridional heat transports for poleward extremes taken in two subsets of the considered period: (left) JJA in 2010, characterized by the occurrence of the Russian heat wave, as described in the manuscript, and (right) JF 2010, coincident with the Mongolian Dzud cold spell event. For each row, extreme events captured at different latitudes (30-33, 45-47, 57-60 bands) are selected, as in Figures 9 and 10 of the manuscript. Transports are shaded in gray where significant, according to a 1-sigma significance level.

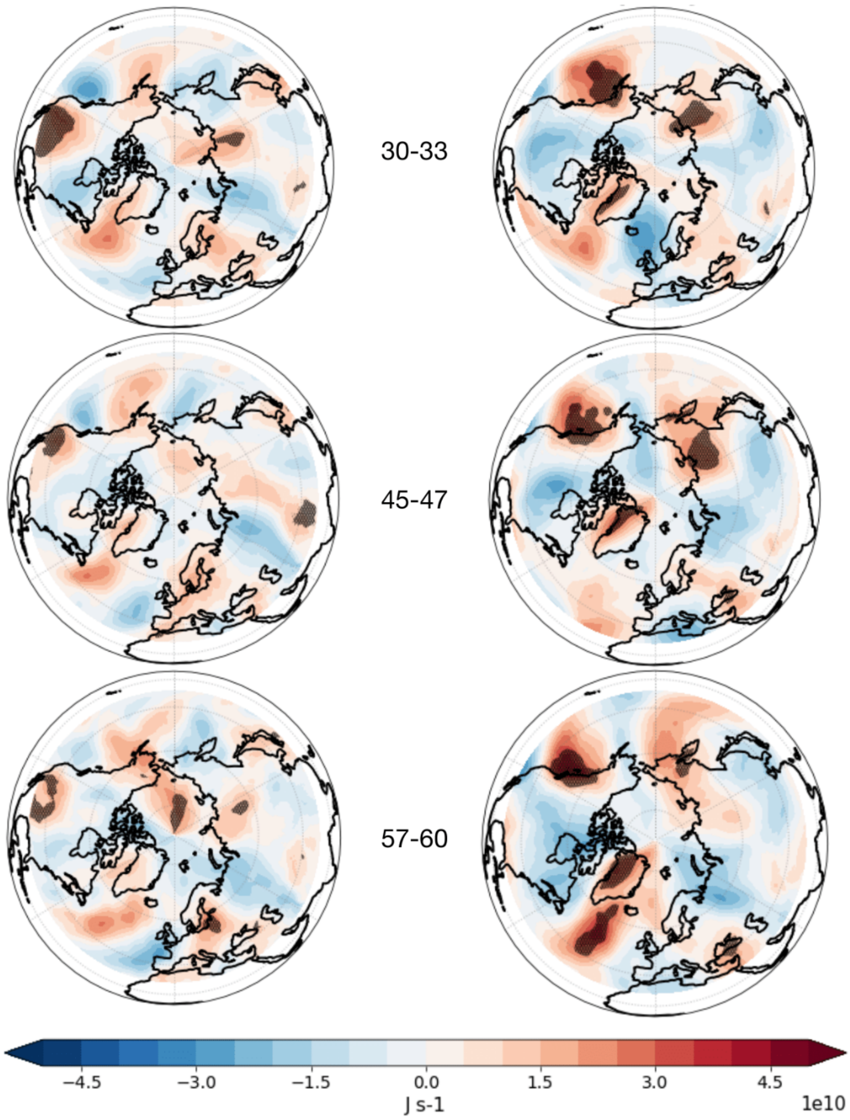


Figure R4: Time mean of meridional energy transports for poleward extremes in the 30-33 (top), 45-47 (middle) and 57-60 (bottom) latitudinal bands, selected according to the algorithm described in the manuscript, for the JJA 2010 (left) and JF 2010 (right) periods. Areas with mean transport exceeding 1-sigma standard deviation are shaded in gray.

It is clear that, even for such a small subset for events (ranging between 40 and 100 for each of the latitudinal band and tail), a direct attribution of extreme events is difficult, and significant regions are relatively geographical constrained, though informative, in some respects. For instance, extreme events for all three bands are characterized by significant positive (poleward) transports in Central and Western North America, denoting a teleconnection pattern that is consistent with the wave 5 pattern evidenced in Kornhuber et al. 2020. Looking at the Dzud event, a poleward transport emerges in the Northern Pacific and Northern Atlantic up to Greenland. That is fairly consistent with a dynamical pattern denoted by negative geopotential anomalies over Siberia and Mongolia, and an equatorward advection of cold air from the Pole affecting large portions of central Asia.

Discussion

Comments on QRA and heatwaves:

L302-328: Authors argue that the heat waves are related to the poleward energy transport and present the year 2010 as an example of the extreme poleward energy transport. I found this interpretation is somewhat subjective and lack of dynamical justifications.

My first concern is the choice of the sample. It looks like the energy transport in JJA, according to Fig. 8, is generally associated with the wavenumber 4 to 6. Accordingly, I would expect to find out energy transport to be associated with wavenumber of 4 to 6, regardless of the year. Therefore, the fact that dominant wavenumbers of the energy transport in 2010 is similar to the preferred zonal wavenumber of the quasi-resonant amplification (QRA) theory does not necessarily mean that the energy transport and QRA theory are dynamically connected.

We apologize with the reviewer for the possible misunderstanding: the aim here is not to draw a conceptual link between the QRA mechanism and the existence of poleward meridional energy transports in 2010's JJA. The aim is actually pointing out that:

1. the fact that wavenumbers 4-6 dominate the transports in these events is coherent with Petoukhov-Kornhuber findings about QRA mechanism as an explanation of co-recurrent heat waves in the Northern Hemisphere.
2. the 2010's JJA persistent event is a "typical" extreme event for meridional energy transports in summer, and this motivates looking into the "typicality" of such extreme events, as this opens the possibility to exploit some crucial properties of dynamical chaotic systems, as already pointed out for heat waves and cold spells analysis in the framework of large deviation theory (cfr. Galfi et al. 2019.; Galfi and Lucarini 2021) This is already mentioned at ll. 324-328, but it will be clarified in the revised version of the manuscript;

To this extent, it is not our aim here to establish a dynamical linkage between extreme meridional energy transport events and co-recurrent heat waves in the mid-latitudes. We believe that this would require substantial additional analysis that goes beyond the scope of our work. Rather, we want to emphasize that these extreme events are consistent with a set of typical dynamical patterns, and the recurrence of these patterns deserves further investigation.

Also, according to the Figure 11, the extremes are computed with respect to 2010 mean, but shouldn't they be computed with respect to the climatology?

The computation of anomalies has been explored in different ways. In order to account for the trends that are shadowing the patterns of variability, we resolved ourselves to the 2010 seasonal mean. As we agree with the reviewer that this might be a source of confusion, we will provide instead a revised version of the composites, with anomalies computed wrt. a detrended seasonal mean over all years.

The second question is the actual dynamical connection between energy transport, QRA mechanism, and heat waves. If I understand correctly, QRA mechanism requires a zonally oriented enhanced jet stream that can act as a strong waveguide. In line with the comments made earlier, with such a zonally oriented background flow, it is little unclear to me how meridional energy transport can be strong. In addition, heat waves are rather caused by processes such as temperature advection, enhanced solar radiation within an anticyclone, and etc. So, if you can discuss how meridional energy transport can dynamically cause (or be associated with) the heat waves, it will help readers to follow the manuscript.

We thank the reviewer for pointing this out. We will add a few sentences suggesting what the possible mechanisms linking QRA and meridional energy transport extremes could be. As mentioned in a previous comment, it is not the main scope of this work drawing such dynamical connection. Despite that, we notice that Petoukhov et al. 2013 already stresses that the quasi-resonant hypothesis is associated with weakened zonal components of the circulation by high-amplitude waves (in their case k=6-8, cfr. their Figure 2), and the authors themselves claim that, "as distinct from Branstator's mechanism, the action of the quasi-resonance mechanism essentially depends on the shape rather than the magnitude of the circumglobal jets." This does not exclude, then, that the QRA mechanism can be associated with extremely strong meridional energy transports. As above, expanding this argument, looking at the dynamical linkages between energy transports, temperature (and moisture) advection in the context of co-recurrent heat waves amplified by QRA mechanism, goes beyond the scope of the work here presented.

Other Comments:

- L329: It is confusing how composites based on the 30-33 band and 57-60 band can be characterized by negative NAO. The 30-33 band composite is more zonally oriented without a prominent anticyclonic feature over Greenland, and there are almost no signals in the composite by 57-60 band.

We thank the reviewer for pointing out this inconsistency in the interpretation of Figure 10. We actually noticed that there was an error in the panels 30-33 and 45-47 of the equatorward side. We have corrected it (as shown in Figure R5) and will upload it in the revised version of the manuscript. We apologize for this mistake. The significance level that we have now introduced helped us to emphasize that the composite maps are the blend of different configurations, of which only the 45-47 features a clear NAO- pattern. Same for the PT pattern, with the North American ridge possibly emerging at all latitudes, but the Pacific trough only significant in the 45-47 band. It was already evident in a previous work (Lembo et al. 2019) that meridional energy transport extremes feature a remarkable latitudinal extension, but often do not extend to the margins of the latitudinal band (cfr. Figure 1f). This is also reflected in Figure 5a,e. As we will try to better argue in the revised Discussion section, this is a clear example of how, relying on well-established clustering methodology, using (at least in the case of DJF) a well described set of weather regimes, we are able to correctly interpret composite maps of geopotential height anomalies when zonally integrated meridional energy transport extremes occur. This provides a first, though methodologically reasonable, in our opinion, attempt to draw a linkage between the dynamics of the mid-latitudinal eddies and the transport extremes.

- Decomposing the zonal wavenumber of the energy transport into planetary and synoptic scale is an interesting, and perhaps, an important point, yet their dynamical origin is not discussed well. Therefore, I think the paper can have a broader impact by adding some more discussion on this topic. What are the causes of the planetary vs. synoptic scale meridional energy transports? Is it possible that planetary scale wave and energy transport can be excited by tropical forcing, whereas the synoptic scale waves can be associated with high-frequency transient eddy fluxes? If one can speculate the cause of those energy transport at different zonal scales, it might be beneficial to diagnose the variability and intraseasonal fluctuations of meridional energy transport and perhaps the long-term changes under anthropogenic warming. I will let the authors to decide whether to add a discussion on this topic.

We thank the reviewer for the useful suggestion. In a previous paper (Lembo et al. 2019), the authors argued that the planetary-scale meridional energy transports were of very different nature in the two hemispheres. In particular, we found that planetary-scale waves in the Southern Hemisphere were well present in the wintry season, and they could only be explained in terms of transient waves; this could be seen only via wavenumber decomposition, whereas the classic stationary-transient decomposition was not capable of doing that, with stationary transport almost negligible in the Southern Hemisphere. Recently, Shaw 2014 found that planetary waves have a peculiar role in the abrupt seasonal transition of the Northern Hemisphere, with a SST threshold governing the latent and momentum transport, thus potentially involving the seasonal development of monsoons. This suggests that an in-depth analysis of the dynamical mechanisms leading to the development of planetary waves, and its interaction with synoptic-scale waves, would involve breaking down the moist static energy into its components (dry static energy component and latent energy), an explicit consideration of moisture transport, and of course a proper selection of the wavenumber in terms of the wavelength that is actually representing the process. Parts of these discussions have been carried out in a paper recently under review on WCD, by Stoll and Graversen. This could be a basis to move forward towards an analysis of regional extreme transports, in connection with geopotential, pressure and SST patterns.

Minor comment

- L179: Here, the patterns are based on the time period of 1979-2013, while L62 says that the analyzed time period is 1979-2012. If this is not a typo, then I think it is better to use the same time period for all analysis.

This is a typo which we will correct. The considered period is 01/01/1979-31/12/2012.

- L207, L337, and Figure 11 caption: It is better to spell out ‘with respect to’ instead of just writing wrt.

Thank you for noticing it, we will expand the acronym in the revised manuscript.

- L220 and L222: I think it is better to indicate specific latitudinal band instead of expressing as ‘edges of the mid-latitudinal channel’ or ‘high/low latitude’.

As already mentioned above, we will provide a table of the skewness as a function of the latitudinal bands in the revised manuscript.

- For clarity, it would be good to clearly indicate which figures authors are referring to. For example, L252, “… frequency of NAO-(Fig5a), AO(Fig.5e), and PT (Fig. 5c)” and L253 “In JJA, NHC4(Fig. 6e)/EATC2(Fig.6a) …”. Same clarification in other lines will help readers to follow the manuscript better.

Thanks. We will proceed as suggested by the reviewer.

- It is somewhat difficult to remember the physical pattern of all the JJA pattern with the current names (for example, L276 and 278 EATC2 and NHC4 / EATC4, PACC4, NHC3). So, I suggest to re-name JJA patterns with more intuitive or commonly known names as in DJF, or explicitly explain in the text. For example, L276 can be re-written as '...EATC2 and NHC4(Scandinavia blocking-like pattern) ...'.

We were actually thinking of a possible better way to rename the weather regimes in summer. Unfortunately, literature does not help as it did for winter. We believe, though, that any naming based on recognized patterns would be subjective. This is why we prefer staying with the original formalism.

- L381-398: In these paragraphs, references are written without parenthesis. For example, L383 should be written as "... atmospheric features (Galfi et al. (2019); ... et al. (2021))".

Thanks. We will implement this in the revised manuscript.

Figures

- Figures 2 a-d / A1 / A2: I think it might be visually beneficial to use rectangular map instead of circular map if you wish to only plot certain designated domain. This is only a suggestion, so I will let the authors to decide.

We made several attempts on how to best visualize the weather regime patterns. We also tested a rectilinear grid, but we noticed that it was overrepresenting the high latitudes, and it was not very clear what the pattern would be at the mid-latitudes. Further, as we needed to plot 4*3*2 maps, rectangular plots would have forced us to spread the information on several figures. Also, it would not have been immediately clear what is the regional domain where the k-mean clustering would be performed. For these reasons, we finally opted for the polar projection.

- Figures 3b-e and 4b-c: having a same x-axis range for all four panels will make it easier to compare the relative magnitude of the transport for different wave number regimes. Also x-label should be 'Meridional energy transport', not heat transport.

Thanks. We agree with the reviewer that having the same x-axis range would ease comparison of relative magnitudes. At the same time, though, it would make it more difficult to appreciate the features of the extreme PDFs, where the magnitude is smaller, e.g. Figure 3d. For this reason, we would retain the chosen x-axis range and add, possibly as an inset, or as a different figure, a plot of the relative magnitude of the four wave groups as a function of latitude.

- Figure 9 and 10: (a) and (b) are missing. Also, the unit of color bars in Fig. 9, 10, and 11a are [Pa], which is not [dam].

Thanks. We will correct that in the revised manuscript.

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