

## ***Interactive comment on “Tropical and mid-latitude teleconnections interacting with the Indian summer monsoon rainfall: A Theory-Guided Causal Effect Network approach” by Giorgia Di Capua et al.***

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Response to review #1 The paper is an important contribution to the literature and deserves to be published after some minor alterations. The paper could do more to mention previous literature such as that of Rodwell and Hoskins, which is important in explaining the mechanism for the link between the monsoon, central Asia (including the Ding and Wang region) and further afield to the Mediterranean. In addition, the treatment of what the paper describes as the internal dynamics of the monsoon is confusing. The authors should perhaps re-examine this explanation or make a judge-

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ment as to whether this can be better described as part of the monsoon intraseasonal variability. Note that in boreal summer, it would be more appropriate to refer to the monsoon ISO/BSISO rather than the MJO. The paper generally has some very well produced figures. Specific comments can be found below.

- Answer -

We thank the anonymous reviewer for his/her very positive overall feedback and useful suggestions on missing literature, on how to better discuss and compare the existing literature in the context of our work and on how to improve the clarity of the paper. We have included all suggestions in our revised version of the paper, with a particular attention on discussing the analogies and differences that our results show if compared to previous work. We now describe the BSISO in the introduction and discussion section, with a more specific attention to its relation to MJO in summer. We have included the suggested literature in the introduction and we now compare our results in light of previous contributions to this specific topic. A fully detailed answer to each comment is reported below.

Specific comments

Line 35: It is not clear what is meant by the “ISM convective cell”. Is this some sort of mesoscale convective system or an individual cloud? I suggest that some alternative terminology is found. (See also later on line 39.) – Answer – We thank the reviewer for pointing out this unclear terminology. It is indeed more appropriate to substitute the term “convective cell” with the more general term “circulation system” (of the ISM). We have thus made this substitution in the text.

Line 36: “Periods with strong updraft lead to strong rainfall one week later”. Please clarify if this means locally or acting at some distance along the teleconnection. – Answer – We have further specified the location where the updraft is located, see lines 36-37: “Moreover, we identify a negative feedback between strong updraft located over India and the Bay of Bengal and the ISM rainfall acting at a biweekly timescale, with

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enhanced ISM rainfall following strong updraft by one week.”.

Line 37: In your statement, “internal ISM dynamics has the strongest CE of 0.5”, what does this mean in the context of the similar statement earlier that explains the meaning of these value? Effectively you are saying (unless I am misinterpreting the purpose of the CE value), “A one standard deviation shift in the internal ISM dynamics causes a 0.5 standard deviation shift in ISM rainfall one week later”. It is not clear what you are meaning by this. – Answer – The meaning of the CE is correctly understood. We have however specified that here by internal dynamics it was actually meant the updraft identified over the Indian subcontinent and the Bay of Bengal. The new sentence now reads (lines 35-38) “Moreover, we identify a negative feedback between strong updraft located over India and the Bay of Bengal and the ISM rainfall acting at a bi-weekly timescale, with enhanced ISM rainfall following strong updraft by one week. This mechanism is possibly related to the Boreal Summer Intra-seasonal Oscillation. In our analyses, the updraft has the strongest CE of 0.5, while the Madden-Julian Oscillation variability has a CE of 0.2-0.3.”.

Line 43: In the introduction it may be worth also citing the work of Stephan et al. (2019, <https://doi.org/10.1175/JCLI-D-18-0405.1>) who use the CEN technique to examine the CGT/SRP link to the ISM, albeit in the context of decadal variability. – Answer – We thank the anonymous reviewer for suggesting to include this work in our paper. We now refer to this reference in the introduction to highlight how CENs can be applied to study this type of problem, see line 148-151: “CENs can be used to test whether hypothesized links or teleconnections are likely to represent true physical pathways or rather artefacts due to spurious correlations. CEN have been applied to the study stratospheric polar vortex variability (Kretschmer et al., 2016), multi-decadal North Atlantic overturning circulation (Schleussner et al., 2014) and to study the causal interactions between the ISM, the Silk Road Pattern and the monsoon-desert mechanism (Stephan et al., 2019), showing their usefulness in testing existing hypothesis by eliminating those that are not supported by causality .””. We discuss these results more

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in detail in the discussion section, and compare their outcomes with our analysis, see lines 624-629: “Therefore, our work is in agreement with previous findings that show an influence of the ISM latent heat release on north-east Africa arid conditions via the excitation of Rossby waves to the west. However, here we focus on the relationship between the MT rainfall and the circumglobal teleconnection pattern, thus a link from the MT rainfall towards the Saharan region cannot be inferred from this analysis. Moreover, the causal relationship between the north-eastern Indian rainfall and the downdraft over the north-eastern Sahara related to the monsoon-desert mechanism has already been shown (Stephan et al., 2019).”.

Lines 63-64: In the statement, “. . .this thermodynamic perspective [cloud cover etc. acting to cool the surface] is useful to understand the quasi-biweekly variations of the ISM elements locally”, why is the quasi-biweekly time scale of particular interest? In a monsoon regime wouldn't we expect CAPE to build up and be destroyed much more regularly than this, e.g. on a daily basis, given that the surface forcing is strong and there is a plentiful supply of moisture? Answer - We agree. Following the also the comments below, we now introduce here the BSISO, and refer to the above described mechanism as a potential local driver of the ISM intraseasonal variability. See lines 64-68: “While this thermodynamic perspective is useful to understand the quasi-biweekly variations of the ISM elements locally, the spatio-temporal variations in the evolution of active and break phases over the Indian monsoon region are known to involve interactions between the wind anomalies and the northward propagation of the major rain band anomalies of the Boreal Summer Intraseasonal Oscillation (Chattopadhyay et al., 2009; Shige et al., 2017; Wang et al., 2006). ”.

Line 77: Rather like the earlier comment, what is meant by a “convective cell” of the MJO here? – Answer – Corrected sentence lines 84-85: “Normally, only one region of strong convective motions related to the MJO is present in these regions.”.

Line 87: Regarding “downstream”, careful to specify what is meant. Do you mean downstream with respect to the jet, i.e. further east? This seems to be in the same

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direction as given in the previous sentence, rather than "on the other hand" as the sentence starts. – Answer – We thank the anonymous reviewer for carefully reading the manuscript. We have changed the structure of the paragraph and we now discuss separately the DW2005 and DW2007 related mechanisms in lines 90-107 and 116-131 respectively, this should improve the readability of the paper.

Line 166 onwards: the methods in this section are explained well given the complex techniques involved and the referencing is done very well.

Figure 2 and others in the paper are very inventive and generally of very good quality.

Line 205: How are the "northern mid-latitudes" used for the EOF calculation defined? – Answer – We have clarified this point as follows (see lines 268-269): "Panels (a) and (b): EOF1 and EOF2 expressed as covariance for the JJAS weekly Z200 field in the Northern Hemisphere (0°-90°N, 0°-360°E) for the period 1979-2017."

Line 205: "lag = -1 week". It would be better to clarify exactly which variable is leading the other, to avoid ambiguity. – Answer - We have clarified this point as follows (see lines 269-271): "Panel (c): correlation between weekly MT rainfall (lag = 0) and Z200 (lag = -1 week). Panel (d): the CGTI region (white box) and the correlation between CGTI and Z200 (both at lag = 0), which forms the circumglobal teleconnection pattern."

Line 224: That the first three EOFs are not mutually separable is somewhat of a mathematical interpretation, but what does it mean in terms of any physical explanation of the EOFs? – Answer - We have clarified this point as follows (lines 287-292): "However, by design EOFs do not necessarily reflect physical patterns (irrespective of whether the individual EOFs are separable or not). They only capture dominant patterns of variability, and here EOF2 is useful since it resembles the wave-pattern in the correlation map and thus it likely results from the circumglobal teleconnection pattern related physics. In general, we cannot a priori exclude an influence of EOF1 on the analysed system (while an influence from EOF2 is expected), therefore we will test whether this is the case in the following part of this sub-section."

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Line 232: Perhaps it would be a good idea to add a further physical interpretation of the Z200 leading MT rainfall by 1 week. Presumably this is a west to east propagation of the signal. – Answer – we have included this comment as follows (lines 298-300): "The arch-shaped structure which is visible in Fig. 2c over Europe and central Asia suggests that there could be a wave pattern propagating eastward from Western Europe and affecting the MT rainfall with a 1-week lag. This hypothesis will be further tested in the next section."

Line 247: Does the global scale mentioned here imply that the correlation was performed over all global grid-points? It seems a bit excessive and could probably just be done over the hemisphere. – Answer – We thank the anonymous reviewer for this remark, we did mean that the spatial correlation and the EOFs are calculated only over the Northern Hemisphere and we have corrected this ambiguity (see lines 277-279).

Line 275: Here (and also for the benefit of later), please clarify that the lags of 1-week act in the direction of the arrows (e.g. CGTI leads MT by one week, and then MT feeds back on CGTI one week later). – Answer – We have clarified this point including the text the following sentence, (see lines 356-358) : "Note that the causal effect here is always acting in the direction of the arrow with a lag of one week, e.g. the arrow from CGTI towards MT rainfall represents a causal effect of xx (given by the color) from CGTI to MT rainfall with a lag of one week."

Line 281: Consistency with Ding and Wang is mentioned here, but ultimately this also supports Rodwell and Hoskins (1996) on monsoon-desert coupling (<https://doi.org/10.1002%2Fqj.49712253408>). This seems to be a surprising omission from the paper given that it helps explain the relationship between the monsoon and Ding & Wang region, and ultimately further afield to the Mediterranean. It would be good to discuss this work in the introduction and perhaps see also the works of Cherchi et al. (2014; <https://doi.org/10.1175/JCLI-D-13-00530.1>), which examines the issues in coupled models, and also see the discussion of the Rodwell and Hoskins mechanism in relation to Ding & Wang in Beverley et al. (2019; <https://doi.org/10.1007/s00382->

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018-4371-4). – Answer – We thank the anonymous reviewer for suggesting to include the discussion of the monsoon-desert mechanisms in our work, we now discuss all the suggested references in the introduction, lines 108-115 “The latent heat released via strong convection in the ISM region has also been shown to influence regions which are located upstream (i.e. eastward). The so-called monsoon-desert mechanism involves long Rossby waves to the west of the ISM region generated by ISM latent heating. These waves enhance the downward flow over the eastern Mediterranean and north-eastern Sahara Desert suppressing precipitation in these dry regions (Rodwell and Hoskins, 1996). A subset of CMIP5 models is able to capture this mechanism (Cherchi et al., 2014) and CMIP5 scenarios for the 21st century project increased ISM precipitation, despite a decrease in the strength of the ISM circulation. Thus the monsoon-desert mechanism could contribute to drying and warming trends projected for the eastern Mediterranean region, exacerbating the desiccation conditions in these regions (Cherchi et al., 2016)” and lines 103-107 “Seasonal forecast models, e.g. from the European Centre for Medium-Range Weather Forecasts (ECMWF), tend to have difficulties reproducing this pattern correctly: the circumglobal teleconnection pattern is too weak in models and one of the possible causes could be a too weak interaction with the north-western India rainfall (Beverley et al., 2019). ” as well as in the discussion on the paper lines 622-625 “Moreover, the larger CGTI region as defined in Fig. 4c, while showing the strongest correlation over the CGTI region as defined in Fig. 2d, also stretches south-westwards towards north-east Africa, to the area that features the downdraft related to the monsoon-desert mechanism (Rodwell and Hoskins, 1996). Therefore, our work is in agreement with previous findings that show an influence of the ISM latent heat release on north-eastern Africa arid conditions via the excitation of Rossby waves to the west.” and lines 679-685 “While previous studies that have analysed the relationships between the ISM and the mid-latitude circulation have often considered the rainfall over north-western India (Beverley et al., 2019; Ding and Wang, 2005; Stephan et al., 2019), here we take into account the MT rainfall, showing that connection between active and break phases of the ISM (by definition

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identified over this region, Krishnan et al., 2000) and the circumglobal teleconnection pattern. The circumglobal teleconnection pattern is an important source of variability for European summer weather, thus improving its representation in seasonal forecasting models could in turn improve seasonal forecast in boreal summer (which generally show lower skill than those for boreal winter) (Beverley et al., 2019).”.

In figure 4, panel (d) seems rather pointless. Can a composite difference of ISM rainfall not be given based on the precursors illustrated in the earlier panels of the figure? – Answer – The purpose of this panel in Fig. 4 is only to help the interpretation, as it helps to visualize which region is acting on each response variable at any given lag. lags

Line 326: What do the black contours represent in the figure? – Answer – We have clarified this point as follows for both Fig. 4 and Fig. 6 (lines 275 and 409): “Regions with correlation values with a p-value of  $p < 0.05$  (accounting for the effect of serial correlations) are shown by black contours.”.

Lines 330-332: It may be worth citing some earlier works linking NAO and monsoon, e.g. Goswami et al. (2006, <https://doi.org/10.1029/2005GL024803>). – Answer – We thank the anonymous reviewer for suggesting this useful reference. We now cite this work in the introduction, see lines 117-121: “At inter-decadal and interannual timescales, SSTs related to the Atlantic Multi-decadal Oscillation (AMO) index have been shown to modulate the strength of the ISM by an atmospheric bridge involving the North Atlantic Oscillation (NAO) index: positive (negative) NAO phases modify westerly winds and associated storm tracks in the North Atlantic/European area, and modify tropospheric temperatures over Eurasia, thus enhancing (weakening) strength of the ISM rainfall (Goswami et al., 2006).”. We have also included this reference in the discussion section, see lines 619-621: “This wave pattern is visible in geopotential height fields, temperature and precipitation anomalies, and acts on MT rainfall via the CGTI with a 1-2 week lead time, in agreement with the DW2007 hypothesis and with previous studies showing that there is a connection from the North Atlantic toward the

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ISM system (Goswami et al., 2006).”.

Line 348: The “Himalayan plateau” is not appropriate as it does not exist. Do you mean the Himalayas or the Tibetan Plateau (or both)? Better to think of a more appropriate term. – Answer – We thank the anonymous reviewer for noticing this mistake. We indeed meant the Tibetan Plateau and we have now corrected this mistake (see line 432).

Line 351-355: Rather than the “ITCZ”, isn’t an interpretation of this that the one week earlier than strong rain over the trough, we have rain further south over India, such that we have a northward propagation of the BSISO? The rainband looks slightly tilted rather than entirely zonal. That would be why you see a causal relationship of MJO2 to W1. – Answer – We thank the anonymous reviewer for this insightful suggestion. We now refer to the BSISO instead of to the ITCZ, see lines 434-436: “OLR1 spatially overlaps with W1, the largest causal precursor in the vertical wind field, representing the north-west/south-east tilted rainfall band related to the BSISO over the northern Indian Ocean and western Pacific Ocean (Fig. 6b, top panel).”.

Lines 369-370: There was an explanation on the use of OLR earlier, so it isn’t needed again. – Answer – We thank the anonymous reviewer for pointing out this repetition, which we have now removed.

Line 372: Here and elsewhere we are referred to the internal dynamics of the monsoon. Is this not perhaps better explained as the intraseasonal variability, in other words related to the BSISO of active and break phases? – Answer – We thank the anonymous reviewer for this insightful suggestion. We now refer to the interannual variability and the BSISO instead, see lines 458-460: “The CEN built with OLR1, W1 and the MT rainfall at weekly timescale (Fig. 6c) represents the intraseasonal variability of the monsoon cell and its relation with the BSISO and the initiation of active and break phases.”.

Lines 373-374: The stronger MT rainfall followed by weaker ascending motions one

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week later is probably consistent with a monsoon active phase moving into a break. – Answer – We have now included this suggestion in our manuscript, see lines 466-469: “Thus, from a physical point of view, this can be explained in two ways: (1) as a seesaw representing the switch of the ISM system between an active and a break phase and (2) via an increase of atmospheric static stability due to latent heat release in the higher layers of the troposphere.”

Line 377-380: The negative feedback described here is logical in the sense that convective rainfall acts to stabilize the atmospheric column (and destroy CAPE). But in the monsoon regime, CAPE will quickly be reinvigorated given the surface forcing and good availability of moisture, possibly within a day. Rather than a negative feedback, couldn’t one also argue that (as in Gill’s off-equatorial heating), the LH release of the monsoon convection leads to a feedback and strengthening of the flow. What you are seeing here may instead be better explained as part of the migration between states of the BSISO. – Answer – We thank the reviewer for this insightful comment, here (and later) we now discuss the BSISO as a possible explanation of the presence of a negative feedback between W1 and the MT rainfall, see lines 357-360: “W is calculated at 500 hPa and W1 thus represents the ascending branch of the ISM circulation cell and nearby BSISO. The CEN built with OLR1, W1 and the MT rainfall at weekly timescale (Fig. 6c) represents the intraseasonal variability of the monsoon circulation and therefore its relation with the BSISO and the initiation of active and break phases.”.

Lines 454-455: Are the internal variability and the MJO-related part not somehow related, i.e. they are intraseasonal variability of the monsoon. – Answer – We thank the reviewer for this insightful comment, here (and later) we now discuss the intraseasonal variability instead of the internal dynamics, see lines 470-472: “In this study, we apply causal discovery algorithms to analyse the influence of global middle and upper tropospheric fields on the ISM rainfall and study the two-way causal links between the mid-latitude circulation and ISM rainfall, together with tropical drivers and ISM intraseasonal variability.”.

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Lines 461-462: Monsoon-desert coupling could be mentioned here. – Answer – We thank the reviewer for this useful suggestion, we now include the monsoon desert mechanisms in the discussion section, see lines 620-623: “Moreover, the larger CGTI region as defined in Fig. 4c, while showing the strongest correlation over the CGTI region as defined in Fig. 2d, stretches south-westwards towards north-east Africa, to the area that features the downdraft related to the monsoon-desert mechanism (Rodwell and Hoskins, 1996; Stephan et al., 2019).”.

Line 478: The description here of internal variability dominating over interannual variability might be better explained in terms of intraseasonal versus interannual. – Answer – We have included this suggestion in lines 644-626: “The reported findings are in good agreement with the existing literature. It is well known that internal intraseasonal variability dominates ISM inter-annual variability (Goswami and Xavier, 2005; Suhas et al., 2012).”.

Lines 485-486: It would have been useful to have these discussions about the ITCZ migration earlier. This might be better explained in any case in terms of the switch between break and active phases of the BSISO, as the region of maximum rainfall propagates northward from the equatorial position during a break to Indian latitudes during an active phase. – Answer – We have included this suggestion and we now discuss the BSISO link to the MT rainfall already in lines 605-610 “Next to the influence of the MT rainfall, our analysis also shows that the link between the circumglobal teleconnection pattern and the ISM can be seen in the wider perspective of the BSISO variations. Our OLR1 and W1 regions (see Fig. 6a,b) show a north-west/south-east tilted rainfall band that shows great similarities with the BSISO rainfall band (Wang et al., 2018). In light of this relationship, the negative feedback that characterizes the causal links between W1 and the MJO2 (see Fig. 6d) and the MT rainfall and W1 (see Fig S18, in the SI) can be interpreted as the shift of the ISM system between a break and an active phase and to the north-eastward propagation of BSISO convective anomalies.”.

Line 489: Here and elsewhere, the MJO is discussed but it may be better to think

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in terms of the BSISO, which is the summer manifestation of the MJO with northward propagation. Answer – We have included this suggestion throughout the whole manuscript and we now discuss the BSISO together with the MJO. Moreover, we also discuss evidence that the OMI index we use to describe the MJO, is also useful to describe the BSISO, see lines 87-89 “However, during boreal summer, the MJO strength is reduced as compared to boreal winter, and both the MJO and the BSISO propagation and phases can be well described by the outgoing longwave radiation MJO index (OMI) (Wang et al., 2018).”. In the discussion section, we now also include the discussion of the BSISO next to the MJO, see previous comments for an example.

Line 499 (and elsewhere): It would be better to expand acronyms such as RG-CPD or explain again what they are in the conclusions, for the benefit of the reader that goes straight to the conclusion section. – Answer – We have included this suggestion in the discussion and conclusion section of the paper.

Spelling, grammar & other trivia Line 34: Change “influences back” to “feeds back on” – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 63: “in support of suppressing” is rather contradictory English. I suggest changing it to something like, “which tends to suppress convection”. – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 76: Insert “The” before “MJO”. – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 103: It would be customary for a few sentences here at the end of the introduction listing what sections are to follow in the remainder of the paper. – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 125: missing space before “algorithm”. – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 188 and elsewhere: Perhaps put the year of the Pai et al. reference here and elsewhere. – Answer – We thank the reviewer for carefully reading the manuscript, we have now included

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this suggestion in the paper. Line 208: In describing panel (e) it would be clearer to express this as a composite difference, e.g., “Composite temperature difference between weeks with...”. – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 232: timescale → timescales – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 240: patter → pattern – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 243: llink → link – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 262: As in the earlier comment, it might be best to explain as a composite difference. – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 318: “figure” for the new sentence should be capitalized. – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper. Line 479: Enables to → enables us. – Answer – We thank the reviewer for carefully reading the manuscript, we have now included this suggestion in the paper.

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