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Comment

Interactive comment on “Discussing the role of tropical and subtropical moisture sources in extreme precipitation events in the Mediterranean region from a climate change perspective” by S. O. Krichak et al.

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Received and published: 22 September 2015

General remarks

Introductory comments

The last decade has been characterized by a growing understanding of a persistently critical role of the exports of air moisture from the tropics and subtropics in the formation of the cold season extreme precipitation events (EPE) in the Mediterranean

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region (MR). The progress is in line with that in the investigation of disastrous flooding events in Western Europe and other regions of the world. The exports are typically taking place in narrow elongated zones characterized by high water vapor content and strong winds in the lower troposphere referred to as “atmospheric rivers, ARs”. Although the issue of the MR EPEs and inducing them atmospheric conditions has already been widely addressed (e.g. Dayan et al., 2015 - doi:10.5194/nhessd-3-3687-2015 – also submitted to the current special issue) a concise summary of the major research achievements in the understanding the role of the tropical/subtropical exports and ARs in the climatology of precipitation events of above normal intensity in the MR is still missing. The current review addresses the issue by discussing major trends in the investigations performed during the last three decades. The studies show that in spite of significant differences between the different parts of the MR, the exports of large amounts of sub-tropical and/or tropical moisture entering the coastal area during the landfalls of ARs may be seen as a critical factor responsible for the exceptionally intense precipitation during EPEs over the MR. The progress in the understanding the role of ARs in the MR EPEs also allows a new perspective for projecting future climate changes in the MR which appears especially important since contemporary global climate models still cannot adequately capture the frequency, intensity, tendency, and spatial distribution of observed precipitation extremes over large regions in the world. Only a limited number of such evaluations have been performed up to now. Currently existing climate change analyses as well as the modeling studies show that the anthropogenic global warming may lead to stronger and more numerous Atlantic ARs in next few decades. This implies a greater risk of higher rainfall totals and therefore larger winter floods in some parts of the MR accompanied by a greater risk of droughts in the others.

General response to comments by the Referees

In accordance with the recommendations by the referees a major revision of the earlier submitted manuscript has been performed. In particular, to more convincingly and

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systematically present the results we have modified the structure of the manuscript. It consists now of a more detailed Introduction (Section 1); Discussion of research on the determination of major acting mechanisms (Section 2); Presenting evidence on the role of ARs in the MR EPEs (Section 3); Evaluations of the recent past and expected future trends of the MR EPEs (Section 4); and an extensive discussion of the major results and research trends (Section 5). In accordance with the changes some parts of the original text have been transferred to new locations. We have also rewritten the Abstract of the review to better present its goals. The title has also been slightly modified by explicitly indicating the season “cold season”. Additionally, in the Introductory Section a paragraph is now included explaining the focus of the current review as well as our reasons for its inclusion to the NHESS - Special issue on “Climate change, extreme events and hazards in the Mediterranean region”. Some additional minor corrections of the manuscript have also been made to better explain our thoughts on the subject (pg. 4, l. 83 – pg. 5, l. 93). Results of a number of additional studies are now discussed. The list of these additionally discussed or cited studies in each of the sections is as follows.

Section 1: Davies and Pichler 1990; Ramis et al., 1994, 2009; Romero et al., 1998, 1999, 2000; Buzzi et al., 1998; Krichak and Alpert, 1998; Jansa et al, 2000; Kahana et al., 2004; Kotroni et al, 2006; Krichak et al, 2007, 2013; Pastor et al., 2010; Lionello et al., 2012; Pfahl and Wernli, 2012; Navarra and Tubiana, 2013; de Vries et al., 2013.

Section 2: Roebber, 1984; Krichak and Alpert, 1998; Massacand, et al., 1998; Schmith et al., 1998; Sickmoller et al., 2000; Ulbrich et al., 2001; Stohl and James, 2004; Rudari et al., 2005; Sodemann et al., 2009; Gimeno et al., 2010b, 2012; Nieto et al, 2010; Pfahl et al., 2012; Winschall 2012.

Section 3: Doswell et al, 1998; Browning 2004; Dettinger, 2011; Neiman et al., 2011; Liberato et al., 2012; Winschall, 2012; Sodemann and Stohl, 2013; Buzzi et al., 2013; Lavers and Villarini, 2013; Gimeno et al., 2014.

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Section 4: Groisman et al, 2005; Carril et al., 2008; Mariotti et al., 2008, 2015; Hycloj et al., 2008; Vicente-Serrano et al., 2009; Zolina et al, 2010; Gualdi et al., 2012, 2013; Ulbrich et al., 2012; Xoplaki et al., 2012; Barkhordarian et al., 2013; Lavers and Villarini 2013; Givati and Rosenfeld, 2013; Hertig et al., 2013, 2014; Casanueva et al., 2014; Saaroni et al., 2015, Taylor et al, 2012; Baatsen et al., 2015;

Section 5: Baldwin and Dunkerton 1999; Polvani and Kushner, 2002; Kushner and Polvani, 2004; Song and Robinson 2004; Deser et al. 2007; Simpson et al. 2009; Francis et al. 2009; Honda et al. 2009; Garfinkel et al., 2010; 2014 Screen and Simmonds 2010; Smith et al. 2011; Smith et al., 2011; Liu et al. 2012; Francis and Vavrus 2012; Cohen et al. Peings and Magnusdottir, 2014; Feldstein and Lee, 2014; Kim et al., 2014. Cited in original paper version studies and corresponding discussions by Budyko, 1969; Graversen, 2006; Lee et al., 2011; Lee, 2014; Pithian and Mauritsen, 2014; Krishnamurti et al., 2015 are now excluded.

Point to point response to comments by Referees

Responses to Referee #1

1) Recommendation to perform major revision and thoroughly present and systematize the most important knowledge: As is already stated in General Remarks a major revision of the manuscript has been performed in accordance with the recommendation

2) Recommendation to more deeply discuss major issues and to provide additional examples to enlighten the readers on the mechanisms involved As is already indicated in our response to comment 1), the manuscript has been significantly revised. This has allowed us to better focus on discussions of a number of most important issues. In revised version Section 2 presents an extended summary of the research focused on gaining evidence and determination of acting mechanisms. The section provides the reader with a description of major trends in the research starting from the evaluations mainly emphasizing an importance of the effects of topography, upper-level jets, low-level fronts, as well as the sea-atmosphere interactions to identification of a notable

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role for air moisture transported from extra-Mediterranean regions (in some cases in a series of tropical Atlantic storms) and the processes in the MR followed by the moist air mass intrusions. A number of important studies focused on identifying moisture sources in the subtropics or tropics for the MR EPEs are also discussed here. In Section 3 of revised manuscript we present and discuss the evidence on the role of ARs in the MR EPEs. A description of ARs (including the definition) is presented here. An importance of the physical mechanisms in the determination of the total global poleward atmospheric vapor transport is stressed out here. The issue of an importance of the ARs role in the climatology of EPEs in West Europe and the MR is illustrated in the Section based on a number of recent studies. Discussion of the role of water vapor transport to the Euro-MR by cyclones with ARs is performed here based on the Thorncroft et al. (1993) classification of cyclone life cycles (pg. 15, l. 315-pg.16, l. 342). Section 4 of the paper discusses the main results as well as the major directions in investigation of the recent past and expected future trends in climate extremes. A discussion of recent results of the investigations of the role of the variations in teleconnection regimes is also presented here. In this Section we also discuss the results of a limited number of climate modeling studies of the expected future trends in the EPEs strongly associate with those in ARs. In the last Section 5 of the review a summary and discussion of the information presented are given. Still open issues as well as the perspectives of necessary further research are discussed. An analysis of a possible role of the process of melting of Arctic Ice since 1979 in the detected trend in the frequency of days with high concentration of moist air over MENA region is also performed here. Policy relevant recommendations are also provided here.

3) Recommendation to more comprehensively present the evidences and to add new perspectives on the role of the exports of tropical moisture in the MR EPEs As already stated in response to the item 2), in revised paper we provide a deeper discussion of results of the studies focusing on presenting the perspective in the understanding of the role of exports of moist air from tropical and subtropical area in the MR EPEs

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4) Recommendation to avoid superficial expressions: Expressions of this type have been extensively removed in revision. The whole review is aimed on discussing the role of AR in the MR EPEs based on a significant number of already published articles. In the revised version of the paper we made an additional effort of reaching the goal.

5) Recommendation to present figures and other details from cited studies: In accordance with the recommendation we have included a number of additional discussions demonstrating the role of tropical moisture exports and atmospheric rivers illustrated by Figs. 1-4. The paragraph which caused the comment (describing the results by Berto et al. 2004) has been modified and the sentence removed.

6) Recommendation to systematize the examples by presenting overviews on the new insights resulting: As is already notified in response to the comment we have significantly modified the structure of our paper by transferring some of these parts to more appropriate positions in the revised review version. We have also included additional clarifications (pg. 4, l. 84 – pg. 5, l. 94) and added earlier missing references in the Introductory section (Section 1). The Abstract (pg. 2, l. 23-44) and the last part of Section 5 (pg. 30, l. 653 – pg. 32, l. 681) have been completely rewritten. Our original evaluation of the possible role of the Arctic Ice melting in the recent past trends in frequency of days with above normal rains has been also transferred to the Discussion Section to keep our paper as a review (pg. 27, l. 585-pg.31, l. 652). In the other three sections of the revised manuscript, an additional discussion of the examples and overviews of new insights are presented in accordance with the recommendation.

7) Recommendation to present additional figures: Please see our response to the item 5) above first. As already stated above, several relevant figures and discussions are added to highlight the important results. Consequently, we have included (and perform the discussion) in our review five new figures adopted from other publications. In accordance with the recommendation the revised version of the manuscript contains 7 figures. The list of the figures is as follows. Figure 1. adopted from Dacre et al., 2015, Bull Amer Meteorol Soc Figure 2: adopted from Gimeno et al., 2014, Front. Earth Sci

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Figure 3: Fig. 1 in the original manuscript version (redrawn) Figure 4: adopted from Sodemann and Stohl, 2013, Monthly Weather Rev Figure 5. adopted from in Krichak et al., 2015, Theor Appl. Climatol Figure 6: adopted from Gualdi et al., 2012, Regional Assessment of Climate Change in the Mediterranean, Springer, Dordrecht Figure 7: Fig. 2 in the original manuscript version

8) Recommendation to strengthen discussion of the role of the climate change in the MR EPEs: An extensive presentation of the results of investigations of the effects of anthropogenic climate change in the recent past and expected future trends in the frequency of extreme precipitation events and ARs in the MR is given now in Section 4. A discussion and systematization of these findings and research trends are given in Section 5. The test for a possible link between Arctic ice and extreme precipitation events in Middle East – North Africa (MENA) is also presented there.

9) Recommendation to present description of the methodology Krichak et al., 2014 for determination of the frequency of days with above normal precipitation: The description is now provided (pg. 28, l. 597-608)

10) Recommendation to keep the presentation in the form of review: To keep the paper in the form of review in its revised version the analysis of the role of Arctic Ice melting in the climatology of extreme events in the Middle East – North Africa (MENA) area has been transferred to Section 5 (Discussion).

11) Recommendation to modify the discussion - the relationship between Arctic Ice and extreme events is tested only over MENA region: Motivations for performing evaluation on the MENA region are now provided (pg. 21, l. 455-462)

Specific comments

Pg 3985, ln 21-22 – The sentence seems incomplete and out of place R: The sentence has been removed

Pg 3985-86 and discussion of Fig. 1 – The AR is not evident and fully characterized

only from the PW pattern shown in the figure – some further discussion should be presented on the criteria for attribution of an AR (strong winds, length and time criteria). R: The figure (Fig. 3 in revised version) has been redrawn and discussion rewritten Done. Fig. 1 (now Fig. 3) has been redrawn. The redrawn figure allows identification of the AR in accordance with the AR definition. (pg. 13, ll.280-285; pg. 14-15, ll – 304-311)

Pg 3989, ln 6-10 – The sentence is not clear. What do the authors mean by the expression “without triggering a storm earlier”? In this paragraph the authors might further develop the controversial aspects and open issues on this theme which still deserve future research. R: The sentence has been removed. A discussion of the controversial aspects and open issues is now provided in Section 5.

The manuscript has few figures, with poor technical quality. The review would greatly benefit from some extra figures and/or schemes further documenting the AR contribution to MR EPE. R: Done. Fig. 1 (now Fig. 3) has been redrawn. The redrawn figure allows identification of the AR in accordance with the AR definition. Five additional figures adopted from published research articles are now included (Figs. 1, 2, 4, 5, 6)

Responses to Referee # 2

1) Recommendation to perform major revision and discuss additional publications As is already stated in General remarks a major revision of the manuscript has been performed in accordance with the recommendation.

2) Recommendation to add important references which existed in Krichak et al 2015 (The references missing in the original version of the manuscript are now provided) in the revised version.

3) Recommendation to revise the paper by widening the discussion comparing to that in Krichak et al. 2015 In our opinion the paper by Krichak et al., 2015 was indeed an important part of the current review. The original manuscript was built around this paper,

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because for us it was indeed a key reference demonstrating a major trend in the MR EPE research. We agree however that the review must have been modified to allow a wider discussion of different important issues. A major revision of the manuscript has been performed. In particular, to better address the goals we have somewhat changed the structure of the manuscript to allow a more clear and detailed Introduction (Section 1); Discussion of research on the determination of major acting mechanisms (Section 2); Presenting evidence on the role of ARs in the MR EPEs (Section 3); evaluations of the recent past and expected future trends of the MR EPEs (Section 4); and an extensive discussion of the major results and research trends (Section 5). In accordance with the change in this partition, some parts of the original text have been transferred to the new locations. We have also rewritten the Abstract of the review to better present the goals of the Review. The title has also been slightly modified by explicitly indicating the season “cold season”.

As is stated in our response to your 1) results of a number of additional research studies are now discussed in revised paper.

We have added a paragraph to the Introduction explaining the focus of the current review as well as provided our arguments for the necessity of such a Review specially focusing on the cold season EPEs as part of the NHES - Special issue on “Climate change, extreme events and hazards in the Mediterranean region”. Some additional minor corrections of the manuscript have also become necessary to better explain our thoughts on the subject

4) Recommendation to further develop the review in connection to climate change: In accordance with this recommendation the review has been further developed to include the discussions of the issue. in revised manuscript Section 4 presents the main results as well as the major directions in investigation of the recent past and expected future trends in climate extremes. It is demonstrated that the recent evaluations have consistently demonstrate a role of a rise in the transport of tropical moisture to the mid-latitudes in the trends in the frequency of the cold season intense precipitation events in

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western Europe and some parts of the MR. A discussion of recent results of the investigations of the role of the variations in teleconnection regimes is also presented here. An existence of a negative trend in the frequency of days with high concentration of water vapor in the atmosphere over the MENA region during spring is also discussed. In this Section we also discuss the results of a limited number of climate modeling studies of the expected future trends in the EPEs strongly associate with those in ARs. In the last Section 5 of the paper a discussion of the results of performed analyses is presented. An analysis of a possible role of the process of melting of Arctic Ice since 1979 in the detected trend in the frequency of days with high concentration of moist air over MENA region is also performed here. Policy relevant recommendations are also given in Section 5.

Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., 3, 3983, 2015.

NHESSD

3, C1790–C1799, 2015

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