Detailed response to referee J. G. Pinto

We thank Dr. J. G. Pinto for his constructive comments on this manuscript, with which we essentially agree. We have taken into account most of his suggestions. In this letter we explain some of the more important modifications:

"A: In my opinion it is very important to state clearly that Vb cyclones often trigger heavy precipitation on the NORTHERN SIDE of the Alpine range (and Central Europe). In order to have a heavy precipitation event on the southern Alpine range, Vb cyclones are not needed, a deep upper-level trough over the Western Mediterranean and Genova cyclogenesis is "sufficient" (e.g., Martius et al., 2006; Winschall et al., 2012; Pinto et al., 2013). In particular, the primary important of Vb-cyclones for the northern side of the Alps is not clearly stated in the abstract (page 908, line 3), and it should be (it is mentioned later in the paper though, page 922). A related issue has to do with the sentence on page 908, line 11, where it is stated that "only 23% of all Vb events are associated with extreme precipitation (in the Alps)". A Vb cyclone may cause heavy precipitation elsewhere (e.g. Eastern Germany) and comparatively less over the Alps (e.g. 2002 Elbe flood, Ulbrich et al., 2003), and so the statement could be misleading. Please enhance."

This is a very important point that perhaps was not clear enough in the former version of the manuscript. Thus, taking into account this comment, we have enlarged the introduction and the discussion of the results by adding this comment and the suggested bibliography.

"B: The methodology connecting Vb cyclones with precipitation in the Alpine region is currently placed in section 3.2. A clear separation between the methodology and the results would be helpful in my opinion."

We included a new section 2.4 in the methods part to better describe how we define the radius of influence on precipitation of Vb-cyclones. The description of the method has been enlarged to avoid ambiguities and as a result the method description in the results part has been removed. We hope this clear separation of the method and the results will clarify any misunderstanding.

"C: On page 916, line 1-2 the use of spherical cap (23) is not well explained. For example, are the cyclones "rotated" for compositing (e.g. Catto et al., 2010)? On page 918, line 6-11 it is difficult to follow the reasoning about the flexible radius lengths. Since the radius is not always the same the figures it gets a bit confusing. Please state clearly which radius length is shown on each figure (Fig 6, 9, 10, 11)."

The explanation of the method used to calculate the composites has been extended in the new version of the manuscript to clarify this point. Note that all figures show always the same spherical cap, having a radius of 23º. Furthermore, no rotation at all is performed. We have emphasised these two points in the new description of the method. Additionally, we remark now the radius of the spherical cap in each figure caption. We only made use of a flexible radius in combination with the composite tool to identify the precipitation-influencing region of the Vb-cyclones, but not during the analysis of all the other variables. This is now stated in the introduction of the new

method section 2.4 introduced after the suggestion in major comment B.

"D: It is stated in the text that Vb cyclones have a peak occurrence during spring especially in April. Why is this month is not used in the extended summer statistics? On Figure 4 the two PDFs are very similar (or the same?). Instead of using extended summer and winter I would suggest making one figure using the PDF concerning the whole year, and denote the accumulated precipitation of Vb cyclones for all four seasons with different colours (e.g. DJF blue, MAM green, etc). Please enhance and adapt text."

Indeed, the two PDFs in Figure 4 are the same, as they correspond to the distribution over the entire annual cycle, and not for a specific season. This Figure aims at showing the differences between winter and summer, and how they compare to the total distribution of precipitation through the year. In particular, it illustrates the fact that in winter there is not enough moisture in the atmosphere to produce extreme precipitation events, whereas in summer it is able to trigger such events. Note that the analysis of the extreme events in both seasons is beyond of the scope of this study, that rather focuses in the physical mechanisms leading to the remarkably different behaviour in the warm and cold seasons, and in particular in the search for the underlying reasons for the large variability in summer. Furthermore, this Figure shows that the winter season is not able to trigger high precipitation events, and thus winter precipitation is only of secondary importance for impact studies.

We acknowledge that April is the month with the most frequent appearance of Vb-cyclones. Still, we excluded it on purpose from the extended summer season for a number of reasons. The main one is that being in an intermediate season, Vb-cyclones in April exhibit a mixed behaviour, that depending on the atmospheric situation can evolve as a summer-like Vb-event, but more frequently as a winter-like Vb-event. Thus, it is hard to decide beforehand to which extended season April should belong to, since it has to be analysed case by case. Furthermore, one needs to recall that the aim of this analysis is to disentangle the high variability within Vb events, and specially the different behaviour in heavy and weak precipitation events. In doing so, an analysis of the situations needs to be performed in such a way that it minimises the noise introduced by "intermediate behaviour". To do so we decided to analyse the most extreme events, as these are most likely able to highlight a clear signal out of the noisiness produced by the large case-to-case variability and can give a hint on the different behaviour of the atmosphere between these extreme situations. If April is included in this analysis, especially the WPE are impacted by this change. The fact that April cases may behave like winter cases would impact the results of the thermodynamic part, due to the much colder atmospheric state compared to e.g., July. Thus, April cases would blur the signal we obtain without including the April cases. Moreover, the exclusion of April in the extended summer season assures a more or less equal distribution of the months in the 10 WPE and HPE. If April is included there is a strong imbalance between WPEs and HPEs, resulting from a strong bias towards April in the WPEs.

Minor Comments:

"#3: Page 910: it is interesting to note that the authors do not discuss the May/June 2013 event. I am aware that the associated cyclones where not typical Vb-systems

(e.g. Grams et al., 2014), but it would still be worth discussing this here. See also major point A."

We have included a discussion of that reference in the new version of the introduction.

"#7: Page 913, line 24-26: As the authors are surely aware of, this is not always true for Mediterranean cyclones (see results of the IMILAST project that the authors have access to). Please be more specific."

We have reformulated the statement in a more specific way to overcome this caveat.

"#8: Page 914, lines 1-11: Just for interest, was there a reason why local minima of 850 hPa geopotential height were preferred to 850 hPa relative vorticity as the key variable?"

The reason is related to the level of noise and the smoothing required in order to finding meaningful tracks. The Alps is a complex topography feature that introduces large levels of noise into both variables. Nevertheless, since vorticity fields are per se subject to more noise, stronger smoothing is required to be able to obtain reasonable tracks close to the Alps. We made preliminary analysis with both variables, and finally decided that it is more convenient to use geopotential height, which still needs some smoothing as described in the paper, but on a reasonable level.

"#11: Page 915, line 5: how often happens that a cyclone directly cross the Alps? Is the restrictive box really necessary?"

The introduction of a restrictive box indeed reduces the number of detected Vb-cyclones from 95 down to 82 in the 35-year ERA-Interim period. These 13 Vb-cyclones that are dismissed with the restrictive box, move towards the northern side of the Alps in some way, even though they fulfil the criterion of the origin and end box. These trajectories might also be tracked due to artefacts of noise introduced by the Alps. In our opinion, it is important to remove these cases from the list of classified Vb-cyclones, as these would introduce substantial errors in the analysis of Vb-cyclones.

"#15: Page 917, line 21: it is stated "the mature state of the Vb-cyclones is not bound to any box.", but on Fig. 2 an End box is defined. Please explain"

The cyclone does not need to stay inside the end box until it decays. The purpose of these boxes is to guide the cyclone around the Alps, so that it follows the typical Vb-track according to the definition of Van Bebber. But at the same time the boxes should not be too restrictive. The cyclone is able to leave the box again towards the east and thus the mature state of the cyclones is no longer bounded to any box. Thus, once cyclones leave the second box, the paths can divert. We added an additional explanation in the method part to clarify this point.

"#17: Page 920, lines 2-14: see major comment A, a Vb cyclone may lead to a lot of precipitation further north over Central Europe but have limited impact over the Alps."

We absolutely agree on that. We extended this paragraph to include this statement

as well.

"#18: page 920, line 15-21: it is not described how the connection of MED and ATL moisture fluxes to Vb cyclones are defined."

We calculated such fluxes to estimate how much moisture from the respective seas may contribute to the precipitation triggered by Vb-cyclones. Thus, we defined a section through which we guess that most of the moisture might come. Note that although somewhat subjective, the position of these sections is not random. For instance, the Mediterranean latitudinal section has been chosen, as it covers a spot in the Adriatic Sea with high evaporation rate of the ocean water. We included this explanation in the paper and hope that this clarifies the statement.

"#19: Page 920, lines 25-28: What about the possible role of Eastern Europe (e.g. Grams et al., 2014)?"

The moisture source analysis we include in this manuscript is aimed to be a preliminary study and the case-to-case variability is too high between the various Vb-cyclones to draw robust conclusions. The large variability and possibilities of moisture sources hamper finding a common moisture source in this climatological study. Thus, we only address the two most obvious moisture pools, and point out in the outlook that further studies with a RCM are planned, that will allow to carry out sensitivity studies with different SST and soil moisture content. Hopefully this analysis will allow discerning more clearly the sources of precipitation in different Vb-event configurations.

"#23: Page 922, line 3: Fig. 6 and Fig. 11 are very similar, the moisture flux and the wind field at 850 hPa have a very similar pattern. Does it necessary to include both figures? I would suggest removing Fig. 11."

We removed Figure 11 and point out in the text that the wind fields at several levels are comparable to the moisture fluxes with respect to direction and also to relative speed.

"#24: Page 922, line 21: the authors refer to the southern side of the Alps, although the composite figures do not have the geographical references. How does one determine if the precipitation has fallen on the southern side of the Alps?"

It is true that the reader cannot know this, as we do not show the corresponding figures. However, showing this would require including about substantially more figures to the manuscript. Hence, we decided not to show but just to mention this result in the text, emphasising the "not shown" statement. We have clarified this point in the text.

"#31: Page 925, line 18: I would suggest referring to the CORDEX initiative here (e.g. Jacob et al., 2014)."

The CORDEX initiative does not fully fulfil our requirements of simulations. First, the Mediterranean domain does not reach as far north as we would need, whereas the European domain is too big for our interest. Furthermore, we plan to go down to a resolution of 3 kilometres in the innermost domain, which is much finer than the

CORDEX simulations. Finally, we plan to carry out a number of sensitivity simulations that allow emphasising the role of the different aspects of the climate system. Thus, we are not convinced of including such reference here.

We implemented the following minor comments as suggested by the referee:

1: Page 909, line 1: I would suggest using a more general reference(s) here, maybe Kron et al. (2012) and Held et al. (2013).

2: Page 909, lines 5-6: Please rephrase, maybe something like "(. . .) is associated with the occurrence of Vb cyclones"

4: Page 910, line 23: I am not sure if 100% of the Vb cyclones have their genesis in the Genova Gulf, some may for example start earlier. I would prefer to state "main origin area" here.

5: Page 911, line 4: I would also add Giorgi (2006) here.

6: Page 911, line 20-23: See also Zappa et al. (2014).

9: page 914, line 12-27: the filtering of the field and the testing of different geopotential fields could be mentioned earlier, i.e., before the exact chosen method is introduced (around line 3). The lifetime criteria (line 9) would be more logical to appear after the description of the tracking method.

#10: Page 915, line 1: please write "(or not pass)".

#12: Page 916, line 9: I would suggest changing "over Europe" to "over the Mediterranean and Europe".

#13: Page 916, line 17: the notation "15%(14%)" is not clear at first. It would be better if "ERA Interim (E-OBS)" would be mentioned earlier in the sentence. The same applies to the sentence on page 918, line 26-29.

#14: Page 917, lines 12-15 and Fig. 3: the HPEs and WPEs are not yet introduced at this stage. Please indicate you are only discussing the upper panel of Fig. 3.

#16: Page 917, line 25: Please rephrase, awkward start.

#20: page 920, line 28 there is a typo, LPEs instead of WPEs.

#21: Page 921, lines 4-5: Please weaken this statement.

#22: Page 921, line 20: It sounds strange to speak about a "weak depression (at upper levels"). Actually, it is the trough at 300 hPa that is weaker (or maybe a cut-off). Please rephrase.

#26: Page 924, lines 1-14: interesting discussion, please enhance / be more explicit. For example, where is the exact position of the "cut-off"?

#27: Page 924, line 20-25: the results from Zappa et al. (2013) could mentioned here. #28: Page 924, line 27: Please add "towards Europe" at the end of the sentence.

#29: Page 925, line 2: "confirms" sounds like a very strong statement, please weaken, maybe "point in the same direction", or "are in line with"?

#30: Page 925, line 11-12: "(..) in the Alpine region, where (. . .)"

Detailed response to referee A. Speranza

We thank Prof. Dr. A. Speranza for his constructive comments on this manuscript, with which we essentially agree. We have taken into account most of his suggestions. In this letter we address some of the more important modifications:

"Due to orographic and thermal effects closed isobars with gradients exceeding 4 mb over 100 km are found over the western Mediterranean almost one third of the time (1), but most of these depressions are shallow and have no meteorological impact; only a few are associated with deep cyclogenesis (2,3)."

We agree with this remark, and it has been included in the discussion part.

"The proposed statistical procedure is not particularly stable: only 62% of selected Vb-cyclones coincide with those identified by Hofstätter and Chimani (2012)."

We do not fully agree with this statement for two reasons. First, *Hofstätter and Chimani* (2012) used a slightly different method (for example geopotential height at different pressure levels). If eventual disagreements appear, it cannot be judged a priori which method is better, but it has to be elucidated according to more sophisticated criteria than just their agreement. In particular the sensitivity of the method to several parameters is a source of uncertainty, which we addressed in our study, since several methods are evaluated and the most convenient is used in the rest of the analysis. Second, a certain level of disagreement is indeed expected as for example the comparison of Neu et al. (2013) and Raible et al. (2008) shows. Both studies investigate different detection and tracking methods, and the authors found a 40% - 80% of agreement between the different methods. Clearly, the 62% of agreement we report with the Hofstätter and Chimani (2012) findings is included within this range.

"Some authors (4) show that a seasonal change exists in the moisture source for the Alpine regions: predominantly Mediterranean and/or Atlantic in the winter, continental in the summer."

We have considered this comment to improve the introduction. However, the suggested paper analyses precipitation over the Alpine region, separating the Alps in a northern and southern part, but without a clear connection to Vb-events specifically. In our case, we are concerned with Vb-cyclones, which have a northward trajectory, but lead to precipitation in the northern side of the Alps. Thus, it is not apparent which moisture source (predominant for northern or southern Alps) is applicable in this case.

"But the problem should, in my opinion, be studied at more depth. For example, in a recent paper (5) the flooding event over central Europe of June 2013 is analysed in view of some dynamical processes like Rossby wave breaking (RWB) and warm conveyor belt (WCB)."

We agree and think this is an interesting point to analyse. Still, we would like to remark that this study focuses on the Vb-events climatology, rather than on the analysis of each case individually. It is very likely that this phenomenon is very case-dependent, and thus we are a bit sceptical about the scope of the conclusions we can draw with this analysis from a full set of independent storms. For this reason, we have decided not to include this analysis in the manuscript.

"Also the speed of motion of cyclones can be relevant: for example, slow Mediterranean cyclones, having sufficient time to pump up water from the ocean can give rise to very

intense precipitation (6,7)."

This is an interesting point that we have included in the new version of the manuscript. To figure out the relevance of the speed of Vb-cyclones on precipitation, we have regressed precipitation versus speed in all the Vb-events. However, the histograms of propagation speed of the HPE and WPE reveal that, even though the distribution is not completely identical, no clear separation between the two subcategories can be drawn (see Figure 1). This result has been included, albeit without figure, in the new version of the manuscript.

"However, in the present form, the paper is somewhat inconclusive"

By including the analyses proposed by both reviewers, we expect that we may overcome this drawback. Further, in the conclusion part we will point out more clearly how a deeper analysis is indeed already planned for future studies by a RCM. We would like to recall that the main focus in this paper is on a general characterisation of the climatology of Vb-cyclones. However, as there is a very high case-to-case variability, the somewhat inconclusive results are hardly avoidable.
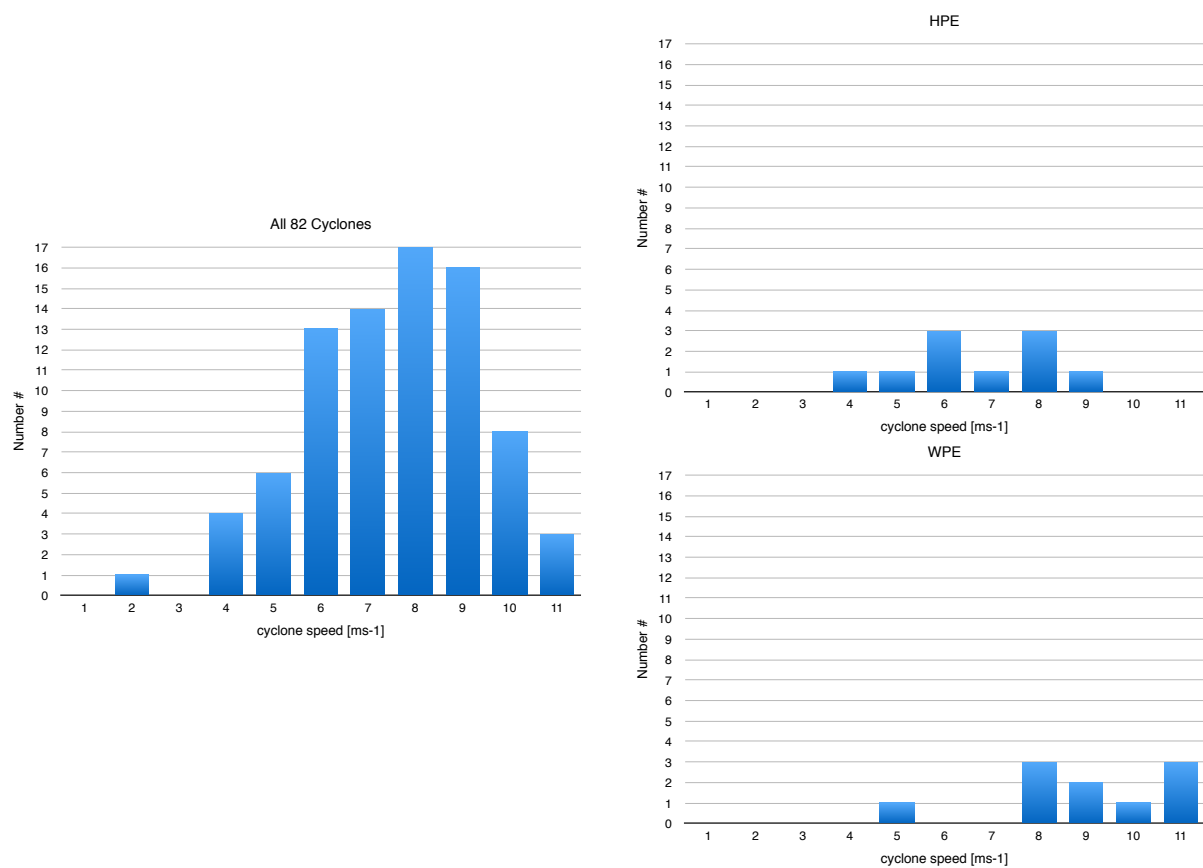

Figure 1: Histogram of cyclone speed is plotted for all 82 Vb-cyclones (left panel), for HPE (upper right panel) and for WPE (lower right panel). Speed is given in ms^{-1}.

Climatology of Vb-cyclones, physical mechanisms and their impact on extreme precipitation over Central Europe

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Abstract. Cyclones, which develop over the western Mediterranean and move northeastward are a major source of extreme weather and known to be responsible for heavy precipitation over ~~Central Europe and the Alps~~the northern side of the Alpine range and Central Europe. As the relevant processes triggering these so-called Vb-events and their impact on extreme precipitation are not yet fully understood, this study ~~focusses~~ focuses on gaining insight into the dynamics of past events. For this, a cyclone detection and tracking tool is applied to the ERA-Interim reanalysis (1979-2013) to identify prominent Vb-situations. Precipitation in the ERA-Interim and the E-OBS datasets is used to evaluate case-to-case precipitation amounts and to assess consistency between the two datasets. Both datasets exhibit high variability in precipitation amounts among different Vb-events. While only 23% of all Vb-events are associated with extreme precipitation, around 15% of all extreme precipitation days (99 percentile) over the ~~Alpine region~~ northern Alpine region and Central Europe are induced by Vb-events, although Vb-cyclones are rare events (2.3 per year). To obtain a better understanding of the variability within Vb-events, the analysis of the 10 heaviest and lowest precipitation Vb-events reveals noticeable differences in the state of the atmosphere. These differences are most pronounced in the geopotential height and potential vorticity field, indicating a much stronger cyclone for heavy precipitation events. The related differences in wind direction are responsible for the moisture transport around the Alps and the orographical lifting along the northern slopes of the Alps. These effects are the main reasons for a disastrous outcome of Vb-events, and consequently are absent in the Vb-events associated with low precipitation. Hence, our results point out that heavy precipitation related to Vb-events is mainly related to large-scale dynamics rather than to thermodynamic processes.

1 Introduction

High impact weather events may have dramatic impacts on society, being a problem that could be potentially enhanced under a changing climate (IPCC-SREX, 2012). Such events lead not only to great economical, but also to personal damage ~~(Donat et al., 2011)~~ (Kron et al., 2012; Held et al., 2013; Donat et al., 2011) . Tropical but also ~~extratropical~~ extra-tropical cyclones can certainly be classified as high impact weather events, as they are associated with extremely strong winds and heavy precipitation that eventually can lead to floodings (Fink et al., 2012; Raible, 2007; Stucki et al., 2014). In Central Europe, and more precisely in the northern Alpine region, a source of high impact events is ~~the so-called Vb-cyclone~~ associated with the occurrence of Vb-cyclones. Such type of cyclone was first mentioned by Köppen (1881), and later defined by Van Bebber (1891) in a cyclone classification based on its characteristic pathway (Fig. 1). The categories were labelled according to Roman numeration from one to five. The Vb-track (a subcategory within the fifth category, and the only one still in use) is associated with extreme precipitation and flash floods over Germany, Austria, Switzerland, the Czech Republic and Poland. The origin of Vb-cyclones ~~are~~ is either the Bay of Biscay, the Balearic Sea or the Ligurian Sea, where moisture uptake occurs. The cyclone moves eastward via Italy and the Adriatic Sea, before it turns northward to the Black Sea or Saint Petersburg. Along this track, orographically induced rainfall takes place on the northern side of the Alps ~~.~~ and its foothills. Note that a Vb-cyclone is normally not associated with heavy precipitation events on the southern slope of the Alps. Heavy precipitation events on the southern side of the Alps can already be triggered by deep upper-level troughs over the Western Mediterranean and by Genova cyclogenesis (Martius et al., 2006; Winschall et al., 2012; Pinto et al., 2013) . Hereinafter the expression "Vb-cyclone" is used for cyclones that follow van Bebber's track.

Despite the destructive potential of Vb-cyclones, literature provides only little information about its characterisation. Most studies on Vb-cyclones focus on case studies. For instance the one-in-a-century flood in August 2002, induced by a Vb-cyclone, has been analysed extensively (Ulbrich et al., 2003a, b; Grazzini and van der Grijn, 2002; Stohl and James, 2004; James et al., 2004; Kaspar and Müller, 2008). A main focus in these studies is the moisture source. Although the Mediterranean Sea is an important source for precipitable water, other studies suggested that the evaporation from land contributes to the precipitation amounts (Ulbrich et al., 2003a; Stohl and James, 2004; Sodemann et al., 2009). Additionally, the Atlantic Ocean and long-range advection of moisture cannot be despised, as demonstrated by Sodemann et al. (2009) using a tracer for water ~~vapor~~ vapour. Another focal point is set on the synoptic-scale conditions leading to the extreme event in August 2002 (Ulbrich et al., 2003b; Grazzini and van der Grijn, 2002). Ulbrich et al. (2003b) suggested a positive interference of several factors that ~~occured~~ occurred in August 2002. These factors include advection of humidity, a quasi-stationary tropospheric trough, inducing upper-level divergence, and orographic lifting of the surface low. Grazzini and van der Grijn (2002) concluded that the anomalous large-scale situation in the summer 2002 and the associated increased cyclone-activity is the main

reason for the devastating floods in August 2002. Other Vb-cyclones that appear as case studies in literature are the cyclone "Axel", in July 2001, which is related to the Vistula flood (Kundzewicz et al., 2005). More important for Switzerland is the Vb-cyclone in August 2005, which led to a very severe flood on the northern flanks of the Alps (Beniston, 2006). The author found that the peak rainfall occurs in August, and is due to a combination of warm ground surfaces and moisture convergence into the Alpine region. Another event happening in June 2013 is associated with cyclones that are non-standard Vb-systems, according to their paths, but nevertheless caused floods affecting the Danube and Elbe catchment (Grams et al., 2014) . The authors recognised equatorward ascending warm conveyor belts as key processes for the heavy precipitation, which are fed by evapotranspiration from soil moisture.

Fewer studies go beyond case studies and analyse a Vb-cyclone climatology. Hofstätter and Chimani (2012) provided an objective catalogue of Vb-cyclones, which allowed the authors to infer that these are only rare events (3.5/year) with a peak occurrence during April. Nissen et al. (2013) focused on the summer half year of a future climate. They projected a decrease in the total number of Vb-cyclones, although their related mean precipitation increases. An extended study, considering the last 500 years of flood history, only found a weak relation between Vb pathways and flood occurrence (Mudelsee et al., 2004). Although there is only little literature specifically focused on climatological Vb-cyclone characteristics, there are several studies devoted to the cyclones in the Mediterranean region, a more general category to which the Vb-cyclones belong to. Trigo et al. (1999) performed an objective climatology of cyclones in the Mediterranean region, concluding that the Genoa region, which is also the main origin of Vb-cyclones, generates most of the cyclones in the Mediterranean region. The authors also stated that topography-controlled cyclogenesis regions account for the most intense events. Fricke and Kaminski (2002) showed that the period from 1881 to 2001, which includes the most extreme precipitation events, reveals a more frequent appearance of the weather pattern "trough over Middle Europe"(Fricke and Kaminski, 2002) . This pattern encloses also the Vb-cyclones. Sodemann and Zubler (2010) analysed a similar, although shorter period of time (1995-2002), focusing on precipitation over the Alps. They determined a seasonal change in the moisture source for both sides of the Alps, i.e. whereas the Mediterranean Sea and the Atlantic Ocean are the major sources in winter for the southern and northern slopes of the Alps, respectively, whereas soil moisture content is predominant in summer. Hence, Vb-cyclones show all the prerequisites needed to trigger high-impact weather events.

Cyclones in the Mediterranean region are frequently analysed under future climate change, as the Mediterranean Basin is a key hotspot of societal vulnerability (IPCC-AR4, 2007) (Giorgi, 2006; IPCC-AR4, 2007) . Unfortunately, there is still no clear agreement on the trend in cyclone number in a future climate. Some studies concluded that there will be a general decrease in number of cyclones during the entire year (Lionello et al., 2002; Nissen et al., 2014) or just in winter (Pinto et al., 2006; Raible et al., 2010), due to either a polar shift of cyclones, a positive shift of the NAO, changes in baroclinic-

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ity or static stability. However, other analyses reported an increase in the total number of cyclones over the Mediterranean (Muskulus and Jacob, 2005; Nissen et al., 2014). The studies also disagreed with respect to extreme events, where Lionello et al. (2002) and Pinto et al. (2006) found an increase, whereas Muskulus and Jacob (2005) and Nissen et al. (2014) found a decrease of extreme cyclones in the Mediterranean. Additionally, Muskulus and Jacob (2005) indicated no significant changes concerning the track properties and precipitation. This is in contrast to Gao et al. (2006), who found a pronounced decrease, especially in summer precipitation, due to an intensified anticyclonic ridge. Nonetheless an increase in precipitation events, especially over and around the Alpine region, can be expected especially in winter according to the study of Gao et al. (2006) due to the fine scale structures in the Alps. Furthermore Zappa et al. (2014) identified two opposing factors in the Mediterranean region, which might be responsible for the large inter-model spread of the CMIP5 models. On one hand these are a general increase in atmospheric moisture content and thus, an increased cyclone precipitation intensity. On the other hand Zappa et al. (2014) found a reduction in precipitation intensity due to a dynamical weakening of the cyclones. The lack of consistency that emerges from these studies illustrates the difficulties involved in climate projections, and point out that a deeper process understanding is important to reduce uncertainties.

As outlined above, only basic climatologies of Vb-cyclones in the past (Hofstätter and Chimani, 2012) and the future (Nissen et al., 2013) have been performed so far. However, a comprehensive analysis concerning the triggering mechanisms driving the extreme precipitation associated with Vb-cyclones is still missing. Thus, in this study we provide a climatology of Vb-cyclones and also explore the physical mechanisms that impact precipitation amounts of Vb-cyclones. The climatology is performed for a 35-yr period using the ERA-Interim reanalysis, whereas the physical mechanisms are studied in more detail for Vb-cyclone subcategories.

The structure of this paper is as follows: Section 2 provides an overview of the datasets and methods used in the study. Section 3 describes the basic climatology of Vb-cyclones, gives insight into the Vb-cyclone variability, and investigates their underlying physical mechanisms. Finally, section 4 provides a summary and discussion of the results, presenting also a short outlook.

2 Data and Methods

2.1 Reanalysis and observational datasets

This study is based on ERA-Interim, a global atmospheric reanalysis data set (Dee et al., 2011) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA-Interim provides 6-hourly estimates of three-dimensional meteorological parameters and 3-hourly estimates for surface variables for the time period between 1979 to present. The ERA-Interim dataset is generated by running the 2006 version of the Integrated Forecast System model of the ECMWF with a resolution of T255 (approximately 80 km) and 60 vertical levels up to 0.1 Pa. The system assimilates

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observational data with a 4-dimensional variational analysis (4D-Var) in a 12-hour analysis window. A number of observational datasets are assimilated in the final product ranging from satellite data to surface pressure observations and radiosonde profiles (see Section 4 in Dee et al., 2011).

In this study we analyse Vb-cyclones for the 35-year period 1979-2013 at 6-hourly resolution. To facilitate the comparison, the 3-hourly forecasted precipitation data is accumulated to 6-hourly data. Furthermore, a vertical integration of moisture in the atmosphere is computed to obtain the total amount of precipitable water. As precipitation data in ERA-Interim is predicted using a forecast model, they are subject to spin-up and spin-down effects that need to be kept in mind (Dee et al., 2011).

Since some important results in this study are based on precipitation amounts, and given that ERA-Interim reanalysis suffers from the aforementioned spin-up and spin-down effects, the precipitation data are compared to the purely observational gridded product E-OBS (Haylock et al., 2008). The E-OBS data are based on weather station data and are interpolated to a 25 km grid. It is a European land-only, daily, gridded dataset. Several variables are available: precipitation, sea level pressure and mean, minimum and maximum temperature for the period 1950 to 2013 (Haylock et al., 2008). As this dataset is based on observations only, there are a number of limitations that need to be mentioned. On the one hand the observations show several inhomogeneities in space and time that populate observational products with uncertainties rendering them mutually inconstant even in areas properly covered by observations (Gómez-Navarro et al., 2012). The spacial inhomogeneity is due to a different density of the observational network of each country, whereas the temporal heterogeneity is based on the varying number of stations maintained by the countries (Hofstra et al., 2009). On the other hand precipitation is especially ~~afffected~~ affected by uncertainties over mountain areas, such as the Alps, our region of interest. Note that the uncertainties are maximal in the summer, as precipitation is driven by convection (Hofstra et al., 2009). This form of precipitation is very local, and thus difficult to capture with the sparse network covering the Alps (Hofstra et al., 2009).

2.2 Detection and tracking methods

In this study we use a tool developed by Blender et al. (1997) that automatically detects and tracks all types of cyclones within a certain area. Thus, in a first step all cyclones that occur over Western and Central Europe during the 35-year time period are retained. Note that ~~there is an overall agreement in climatological characteristics of midlatitude cyclones between~~ different tracking and detection methods ~~(Raible et al., 2008; Neu et al., 2013) .~~

identify comparable characteristics of midlatitude cyclones (Raible et al., 2008; Neu et al., 2013) . For the Mediterranean, different methods show some disagreement in particular with respect to the identified number of cyclone, but agree in terms of location, annual cycle, and trends of cyclone tracks (Lionello et al., in preparation) . The technique has a number of free parameters that allow to adjust the search according to specific purposes. In our case, these parameters are fit to special

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characteristics of Mediterranean cyclones. In particular, since they develop as shallow low-level cyclones, weak gradients must be chosen in order to be able to detect these at the beginning of their life cycle. ~~The position of the cyclones is identified by local minima in the geopotential height at 850~~
~~hPa (z850), taking the eight neighbouring grid points into account. The minimum gradient around a~~
~~cyclone centre in an area of 1000 × 1000 km² is used to focus on cyclones, thus filtering out polar~~
~~and weak minima such as heat lows. For this study we applied a minimum gradient of 25 m/1000~~
~~km. Additionally, a maximum gradient of 50 m/1000 km must be reached at least once during the~~
~~life cycle of a cyclone. The minimum lifetime of each cyclone is set to 24 hours. The minima are~~
~~combined by a next neighbourhood search within a distance of 1000 km. This threshold is chosen as~~
~~it resembles roughly the Rossby deformation radius.~~

Since the Alps introduces disturbances into the geopotential height field, and to remove small-scale and secondary low pressure centres, the input data z850 from ERA-Interim is previously low-pass filtered using a weighted average of 5×5 grid points prior to the analysis of the tracks. The weights are defined according to a Hann-window function. The 5×5 window has been chosen by analysing the robustness of the obtained trajectories after different window sizes are applied in the smoothing (not shown). Similarly, several levels of the geopotential height fields are tested within the detection and tracking technique, using finally the 850 hPa level. The reason is on the one hand to have a balance between the shallow character of Mediterranean cyclones and therefore a level close to the ground. On the other hand, it is hardly possible to find meaningful tracks at the surface, as mountains introduce substantial artefacts into the geopotential height field that render the cyclone tracking more difficult. Tests with several levels and filters have shown that the prominent Vb-cyclones (Alpine flood 2005, Elbe flood 2002, Axel 2001) can be identified in the 850 hPa level in combination with a 5×5 grid point weighted average low-pass filter, so this is the configuration employed through the manuscript.

The position of the cyclones is identified by local minima in the geopotential height at 850 hPa (z850), taking the eight neighbouring grid points into account. The minimum gradient around a cyclone centre in an area of 1000 × 1000 km² is used to focus on cyclones, thus filtering out polar and weak minima such as heat lows. For this study we applied a minimum gradient of 25 m/1000 km. Additionally, a maximum gradient of 50 m/1000 km must be reached at least once during the life cycle of a cyclone. The minimum lifetime of each cyclone is set to 24 hours. The minima are combined by a next neighbourhood search within a distance of 1000 km. This threshold is chosen as it resembles roughly the Rossby deformation radius.

As the tracking tool detects all cyclones, not only Vb-cyclones, the output of this tool has to be further filtered. For this task, we define areas (boxes) where a potential Vb-cyclone should pass (or not ~~to do it~~pass) at least once in its lifetime in order to be retained: The origin box (42°-46° N, 4°-13° E) accounts for the fact that Vb-cyclones, per definition, either develop or intensify over the Mediterranean Sea close to Genoa, while the end box (46°-52° N, 12°-19° E) assures the sudden

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turnaround northward at the eastern edge of the Alps. Note that the cyclone can leave the end box

205 towards the east at the end of its lifecycle. The purpose of the boxes is to guide the cyclones around the Alps. As soon as this task is fulfilled the cyclones can move freely. A third restrictive box (46.5°-55° N, 5°-11.5° E) covering the Alps and the eastern part of Germany is introduced to avoid that cyclones ~~that directly cross the Alps are classified as Vb-cyclone~~ stay at any time on the northern side of the Alps before they move around the Alpine range on its eastern side. These three boxes

210 are displayed in Fig. 2 and are ~~labeled~~ labelled with O for the origin, E for the end and R for the restriction box. Note that ~~this simple criterion is~~ these simple criteria are similar to that described by Hofstätter and Chimani (2012).

2.3 Composite analysis of midlatitude cyclones

A prominent problem when analysing the structure and physical processes related to cyclones is that

215 they do not occur at a fix location, but they are moving objects. Hence, a simple temporal mean becomes misleading due to the different location of the storm. A simple approach to overcome this problem is to use a moving grid whose centre coincides with the storm at each time step. However, this still has a problem when the analysis is performed on a regular latitude-longitude grid (as is the case of ERA-Interim). This is so because the area of each grid box relative to the centre of the

220 cyclone decreases with higher latitudes, so each grid point might be representative of a different area in different time steps if the storm moves northward. This is not a major problem in tropical cyclones, since the effect becomes insignificant near the equator, but it is a matter of concern in the midlatitudes, precisely where ~~Vb cyclones~~ Vb-cyclones evolve. Since this study aims at analysing temporal composites of several variables, or the most precipitation intense time step in different

225 cyclones, this becomes a technical challenge that has to be addressed.

This study applies a composite tool based on the projection described by Bengtsson et al. (2007). The method works as follows. The variable of interest, defined on a latitude-longitude grid, is first remapped onto spherical coordinates in a $0.5° \times 0.5°$ resolution grid, where the cyclone's centre is set in the pole of the grid. This grid extends with a radius of 23° around the cyclone's centre. Hereby,

230 a spherical cap ~~around the storm~~ is obtained for each time step. ~~This cap has an outermost boundary located at 23° off the cyclone centre~~, which is always directed towards the north. Once the variable of interest is remapped onto this grid (which is different for each time step), all regular statistics can be calculated over this variable (means, maximum, etc.), and the results are fully comparable among different time steps and storms.

235 ### 2.4 Selecting the precipitation influencing time steps in the lifecycle of Vb-cyclones

In the following analysis we focus on precipitation triggered by Vb-cyclones. The area of interest for precipitation covers the northern slopes of the Alps, the southern part of Germany, Austria and the southern part of the Czech Republic. This area is depicted in Fig. 2 as a black rectangle. The

beginning and the end of the tracks of the Vb-cyclones can be located, e.g., in the Atlantic Ocean and far up in the north of Poland or even Russia, respectively. If the centre of the cyclone is placed that far away from the black box described above it must be assumed that the cyclone does no longer influence the falling precipitation in this area. Furthermore it is more likely that a different weather feature, like a frontal system, disconnected from the Vb-cyclone, produces precipitation in that area. To omit this we make use of the composite tool described in section 2.3 in a slightly adapted way, such that only time steps are included in the analysis which exhibit a cyclone centre close enough to the region of interest. Thus, the radius of the grid area around the cyclone's centre in the composite tool, which is influenced by the cyclone, depends on the gradient of the cyclone, and thus on its intensity. Hence, Vb-cyclones ascribing a gradient within plus or minus one standard deviation obtain a radius of 6°. Gradients that exceed (fall behind) one standard deviation, 75 (25) percentile or 95 (5) percentile obtain a radius expansion (decrease) of 0.5°, 1° or 1.5°, respectively. Only if this radius is able to reach the precipitation box depicted in Fig. 2, the time step is considered as precipitation contributing. Note that the flexible radius in combination with the composite tool is only used to define the precipitation influencing time steps. For all other variables the composite tool is applied with a fixed radius of 23° as described in section 2.3.

3 Results

3.1 Basic climatology of Vb-cyclones

Vb-cyclones are relatively rare events compared to the frequency of cyclones detected over the Mediterranean and Europe. Applying the tracking approach of Blender et al. (1997) to the smoothed z850 surface, 3448 cyclones are detected over Europe between 1979 and 2013. After filtering out the cyclones with the boxes described in Section 22.2, a total of only 82 cyclones is classified as Vb-cyclones, i.e., only 2.4% of all cyclones in Western and Central Europe. Due to their rareness, the average appearance of Vb-cyclones per year is 2.3, with a mean duration of 3.1 days. Still, the occurrence of these events is irregularly distributed over the 35-year period (for instance up to five Vb-cyclones are tracked in 1979 and 1984, while none is found in the years 1989, 1993 and 2011). However, despite their rareness they considering ERA-Interim (E-OBS) dataset in this period of time the rare Vb-events are responsible for almost 15% (14%) of extreme precipitation days in the Alpine region considering ERA-Interim (E-OBS) dataset in this period of time northern Alpine region and Central Europe. Here, extreme precipitation days are defined as exceedances exceedance of the 99 percentile. Hence, we note that even though Vb-events are relatively rare, they have a great potential to trigger high-impact weather events.

Using a similar approach, Hofstätter and Chimani (2012) reported an annual average of 3.5 Vb-cyclones per year. The climatological probability of Vb-cyclones to appear on any day is 3.8% in their analysis, compared to the 2.0% found in the present study. The potential reason for this

discrepancy is that their method substantially differs from the one used here: different input data,

275   tracking tool, and posterior filtering. Still, 62% of the Vb-cyclones tracked in this study coincide with those found by Hofstätter and Chimani (2012) considering only the overlapping period from 1979 to 2002 of the two studies.

    Beyond the irregular distribution of the 82 Vb-cyclones over the analysed period, they are also not evenly distributed within the annual cycle. Considering the standard seasons winter (December, Jan-

280   uary, February), spring (March, April, May), summer (June, July, August) and autumn (September, October, November) there are less Vb-cyclones in winter than expected from a homogeneous distribution over the annual cycle (p-level < 0.1) and an excess in spring (p-level < 0.05). The fact that Vb-cyclones emerge more frequently in spring has already been pointed out by Van Bebber (1891) and confirmed by Hofstätter and Chimani (2012), which reported a maximum in April.

285   The Vb-cyclones are also characterised by their trajectories. The probability density of all Vb-cyclone ~~centers~~ centres is depicted in the upper panel of Fig. 3 and estimated using a Gaussian Kernel Density Estimator with a bandwidth of $0.6°$. Thus, the shaded area indicates how likely it is that a Vb-cyclone ~~center~~ centre passes through this grid point at any time step. The density illustrates the most common pathways followed by Vb-cyclones, and fits very well the track described by

290   Van Bebber (1891), illustrating why this categorisation is still in use. As expected the Genoa region is most frequently passed by the cyclones, as this region coincides with the origin box. Even a rare Vb-cyclone, which develops in the lee of the Atlas ~~mountain~~Mountains, is detected once. Note that the end of the Vb-cyclone track is more diverse, given that the ~~mature state~~ last time steps of the Vb-cyclones ~~is not~~ are no longer bound to any box. The effect of the restriction box is clearly visible

295   as sharp bend of the orange-coloured contours at the western flanks of the Alps.

3.2 ~~Within Vb-cyclone variability~~Variability within Vb-cyclones

In this section we ~~deepen in~~ enlarge upon the analysis of Vb-cyclone characteristics focusing on remarkable differences ~~within these events~~in particular between these events, particularly with respect to precipitation. Thereby, Vb-events are classified by using a precipitation criterion. For this,

300   the mean precipitation over a box covering the Alpine region is calculated for each time step. The box is depicted in Fig. 2 as a black rectangle. ~~As the detected Vb-cyclones may start and end at locations where they are far off a point to exert influence on the aforementioned precipitation area, the composite tool described in section 2.3 is applied to the precipitation field. This step allows to reduce the influence of other weather features on precipitation amounts on the northern side of~~

305   ~~the Alps. For this analysis, the radius of the cyclone area in the composite tool is adapted from 23° to a more flexible one that depends on the gradient of the cyclone, and thus on its intensity. Hence, Vb-cyclones ascribing a gradient within plus or minus one standard deviation obtain a radius of 6 degrees. Gradients that exceed (fall behind) one standard deviation, 75 (25) percentile or 95 (5) percentile obtain a radius expansion (decrease) of 0.5, 1 or 1.5 degrees, respectively. Only if~~

310 ~~this radius is able to reach the precipitation box depicted in Fig. 2, the time step is considered as precipitation contributing . In the following, the precipitation of these time steps~~ In the following, the precipitation of the precipitation contributing time steps (as described in section 2.4) is accumulated over each Vb-event. Note that this has the disadvantage that the accumulation period differs among various Vb-cyclones, which has to be taken into account in the analysis hereafter.

315 To compare the precipitation triggered by Vb-cyclones to regular precipitation days, the distribution of such precipitation needs to be estimated. As the Vb-cyclone duration differs from one another, the estimation of the precipitation distribution becomes challenging. Hence, a bootstrap method is applied to estimate such precipitation distribution over this particular box ~~,~~ that has to mimic the real distribution of Vb-cyclone duration. The estimation is based on 3 million bootstrap samples of

320 observed precipitation accumulated during a period whose length is selected randomly according to the observed distribution of length of Vb-cyclones. The same method is applied to the ERA-Interim and daily E-OBS dataset to confirm consistency between observational data and forecasted reanalysis data. Figure 4 displays the estimated distribution of precipitation in the box covering the Alpine region for ERA-Interim. ~~In winter~~ Using ERA-Interim (E-OBS, not shown) dataset, only two (none)

325 of the Vb-cyclones exceed the 95 percentile ~~using ERA-Interim (E-OBS, not shown) dataset, while in summer~~ in winter, whereas in summer, 24 (19) Vb-cyclones produce extreme precipitation over the region of interest~~considering ERA-Interim data (E-OBS, not shown)~~. Note that there is a wide variability in accumulated summer precipitation within Vb-cyclones, ranging between almost no precipitation and extreme events. Furthermore, most of the winter events show a narrow variability.

330 For consistency reasons and the sake of brevity only the results for ERA-Interim data are shown hereafter, although it has to be noted that the results for the E-OBS dataset resemble the findings based on ERA-Interim discussed here in more detail. The striking difference between summer and winter is most probably due to the effect of the Clausius-Claperyon equation, which relates air temperature to its ability to carry water vapour.

335 To gain further insight in the characteristics of Vb-cyclones, those related to heavy precipitation events (HPE) and weak precipitation events (WPE) in the extended summer season are analysed in detail. Thereby, the 10 most extreme events with respect to precipitation are selected. Figure 5 displays a composite of the most intense precipitation time step of the 10 HPE on the left and WPE on the right. As expected, the HPEs generate much more precipitation and affect a wider

340 area. Locally, the precipitation amounts are even doubled compared to the WPEs. More interesting is the fact that the HPEs composite shows a precipitation pattern that is expected from Vb-events. The main precipitation falls on the northern flanks of the Alps and extends towards the east as far as the catchment of the river Elbe and Oder, which were the main contributors of the floods in August 2002 (Ulbrich et al., 2003a; Kundzewicz et al., 2005) and thus play an important role

345 in Vb-events. In contrary the WPEs show maximum precipitation more to the east of the Alps. Additionally, there seems to be frontal behaviour that interferes with Vb-cyclones in some of the

WPEs which is illustrated by the long precipitation band in Eastern Europe. It is important to note that even though precipitation patterns are different, the associated PDFs of the trajectories of HPEs and WPEs, depicted in the lower panels of Fig. 3, do not show significant differences. Thus, the trajectory of the Vb-cyclone does not seem to play an important role on deciding whether an event will cluster into the HPE or the WPE subcategories.

3.3 Physical mechanisms driving Vb-cyclones variability

As precipitation amounts are linked to available moisture content in the atmosphere, it makes sense to investigate whether the state of the atmosphere plays a prominent role on the rainfall associated to a Vb-cyclone (Stohl and James, 2004; Sodemann et al., 2009). The precipitable water at the most precipitation intense time step shows a much higher amount for the HPEs, than for WPEs (Fig. 6). Still, the differences around the centre of the cyclone are small compared to the high moisture band further off the centre. The moisture fluxes depicted in Fig. 6 imply that the major part of this moisture is transported straight to the northeast, and thus away from the ~~region of interest~~ northern Alpine region for the WPEs and the HPEs. Note that some of this precipitable water can lead to precipitation further north over, e.g., Eastern Germany. The additional precipitation in the northeast of the box can easily be detected in Fig. 5. This is especially true for the HPEs. Furthermore, the case-to-case variability in precipitable water is relatively large, and indeed some HPE cases contain even less precipitable water than certain WPEs. Hence, precipitable water in the atmosphere is not an unambiguous variable suitable to predict whether a Vb-cyclone would potentially lead to severe precipitation.

A related variable that is in principle more accurate to characterise the differences observed between HPEs and WPEs is the moisture flux through certain latitude sections of interest. This allows ~~to test~~ testing the hypothesis generally assumed stating that Vb-cyclones receive most of their precipitable water from the Mediterranean Sea. Therefore, a latitudinal section over the Adriatic Sea is selected as depicted in Fig. 2 with a stippled black line labelled "MED". This section is chosen, because it is located over a region of high vertical moisture transport. Results of the moisture flux through this section indicate however that no clear separation of the moisture flux across this line between the HPEs and WPEs is possible (left panel of Fig. 7). Thus, this criterion is not suitable to characterise the high-impact related Vb-cyclones. Similarly, a second cross-section over France and Switzerland labelled "ATL" in Fig. 2 allows to analyse the southward moisture flux from the North Atlantic Ocean. As the right panel of Fig. 7 demonstrates, this cross-section enables a slightly clearer separation between HPEs and WPEs than the moisture fluxes across "MED" line. The increased transport of HPEs suggests that a large part of moisture is transported from the North Atlantic, instead of the Mediterranean Sea. Still, no clear separation between the HPEs and the ~~LPEs~~ WPEs is found, especially because it is very sensitive to the exact location of this cross-section (not shown).

Hence, these results indicate that moisture variables alone do not allow ~~to explain~~ explaining the different behaviour observed between HPEs and WPEs.

~~Once ruled out~~ Since the thermodynamic state of the atmosphere ~~as a suitable explanation of~~
385 cannot present a distinct explanation for the within-Vb variability, we turn our attention to the dynamical mechanisms. One reason for the different amounts in precipitation between the HPE and WPE might be the cyclone speed. Fast moving Mediterranean cyclones may not be able to pump up as much water from the ocean than slow moving cyclones. Nevertheless a clear separation in cyclone propagation speed between the HPE and WPE is not successful. Reasons for the deviations
390 in precipitation amounts and pattern among Vb-cyclones are found more clearly in the geopotential height field. Figure 8 reveals that the WPEs overall show a smaller intensification rate than HPEs (p-level < 0.01). Further differences in the geopotential height are found in the spatial structure of the average state (Fig. 9). The HPEs and WPEs show similar features at first glance in the z850 field during the most precipitation intense time step. In both cases a low pressure area is localised in the
395 centre of the storm. This is expected, as this is indeed the criterion used for the detection tool applied in the first step. Nevertheless, there are some important differences. The composites of HPEs exhibit a strong cyclone, as a steep gradient in combination with a deep depression is observed. The fact that the HPEs are triggered by a distinct cyclone is more obvious when considering higher levels, because the depression from the ground extends through the 500 hPa and 300 hPa levels. Another
400 indication for a strong developing cyclone is the westward tilting of the system. This is in contrast with the WPEs, which are induced by a shallow depression. Even though the z850 shows an isolated isobar, this feature is lost at the 500 hPa and appears as a ~~weak depression~~ weakened trough at 300 hPa again. Another important feature is detected in the northwest of the WPEs in terms of a depression. This system seems to coalesce with the original depression, which leads to an asymmetric
405 geopotential height gradient on the southern side of the cyclone centre.

The hypothesis of associating a stronger cyclone with HPEs is underlined when analysing the potential vorticity (PV) at the 325 K potential temperature surface (Fig. 10). For the HPEs, it presents a PV-streamer that is close to a cut-off. This feature is absent in the WPE cases, which show instead a PV maximum in the northwest of the cyclone centre, similar to the situation of the 300 hPa
410 geopotential height field.

The aforementioned differences in the geopotential height fields between the HPEs and WPEs trigger important differences in the wind field in different elevations. ~~Figure ?? shows~~ Note that the wind fields ~~at 850 hPa of the~~ in different elevations are in good agreement with the vertically integrated moisture flux in regard to direction and relative strength. Figure 6 shows that the HPEs
415 experience strong winds on the southern side of the cyclone centre, transporting air masses directly towards the northwest of the cyclone and out of its influence region. More importantly, rotation around the centre of the cyclone becomes apparent. The same features are also visible on the 325 K potential temperature surface in Fig. 10, where air masses are transported towards the northeast due

to its U-shape, whereas the wind system close to the centre rotates. This rotation is highly important
for high-impact Vb-cyclones (HPEs), as moisture needs to be transported around the Alps to produce
orographic lifting along the northern side of the Alps. Hence, orographic precipitation is generated
on the northern side of the Alps. This is supported by the fact that a major part of precipitation
amounts is actually found on the northeastern side of the Alps (not shown) and thus in the region
of interest during the most precipitation intense time step. In contrast, WPEs do not exhibit such
rotating wind field. This is mainly due to the influence of the deeper depression in the northwest of
the cyclones appearing at the same time as the WPEs. The strong gradient, which is maintained at
the southern side of the actual cyclone centre, results in strong U-shaped wind fields that preclude
rotation. Nevertheless, a certain amount of rotation is found above the ground (not shown), which
explains the modest amounts of precipitation found in the region of interest. However, the main part
of the precipitation can still be detected on the southern side of the Alps (not shown), as orographic
lifting occurs there. Thus, the precipitation on the southern side of the Alps is not able to influence
the main precipitation area of Vb-cyclones during the most precipitation intense time step.

4   Discussion and Conclusion

The results concerning the basic climatology of Vb-cyclones show a good agreement with the find-
ings previously reported by Hofstätter and Chimani (2012), i.e., the rareness of Vb-cyclones (2.3
Vb-cyclone appearances per year, the peak of Vb-cyclones in spring and a general agreement of the
exact appearance of 65% of all Vb-cyclones compared to Hofstätter and Chimani (2012). As our
findings seem to be robust with respect to the applied method, our study goes beyond the statistical
climatology introduced by Hofstätter and Chimani (2012) and deepens on the physical mechanisms
in order to understand the large variability within the Vb-cyclone triggered precipitation.

The analysis of the precipitation distribution associated to Vb-cyclones reveals that the cases iden-
tified in the extended winter are not able to trigger extreme precipitation. This fact can be explained
through the application of the Clausius-Claperyon equation. However, summer cases exhibit larger
variability, leading to a number of extreme situations. This motivates a further subclassification
of the summer cases using accumulated precipitation over the northern Alpine region and Central
Europe as classification criterion. Although the moisture content in the atmosphere provides a first
separation between the extended summer and winter Vb-cyclones through the Clausius-Claperyon
equation, it fails to serve as criterion to separate the 10 WPEs and HPEs in the extended summer,
since the inter case variability is too large. Thus, the moisture content in the atmosphere cannot
unambiguously separate the HPEs and WPEs. Also neither the northward moisture flux from the
Mediterranean Sea nor the southward flux from the Atlantic can succeed in disentangling the dif-
ferent behaviour of WPEs and HPEs. ~~We identify~~ The fact that neither the Mediterranean nor the
Atlantic Sea are exclusively responsible for the precipitation brings us to the conclusion, that various

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moisture sources ~~contributing~~ contribute to precipitation in Vb-events~~apart from the Mediterranean~~ ~~Sea, a result that~~. This result is consistent with previous findings reported by Stohl and James (2004), James et al. (2004) and Sodemann et al. (2009) for the one-in-a-century flood in August 2002. The large amount of possible moisture source combinations and the various moisture patterns that are associated to the Vb-cyclones enable us to conclude that the moisture content and source strongly depend on a case-to-case basis and preclude obtaining general conclusions.

In contrast, the variables associated to the large-scale dynamics, i.e., geopotential height and PV at the potential temperature level 325 K, allow a meaningful categorisation of the HPEs and WPEs. The average geopotential height field in HPEs shows a distinct cut-off low extending over the whole atmosphere. Additionally, PV shows a PV-streamer close to a cut-off. These two features trigger a vortex that can be traced in the wind fields. These fields suggest that precipitation is triggered by a northerly Alpine inflow. Thus, most of the precipitation falls on the northern to ~~north-eastern~~ northeastern side of the Alps. Similar situations ("pivoting cut-off") have been found by Stucki et al. (2012) in the context of past extreme floods in Switzerland. Hereby the cut-off low is located over the Adriatic Sea and is near-stationary due to blocking surface highs, located over western and eastern Europe. Also Zängl (2004) identified the orographic enhancement as important trigger for the high precipitation records in August 2002. The WPEs in contrary are only associated with weak low pressure systems that do not elongate through various atmospheric layers. Also PV reveals only an initial state of a PV-streamer. Hence, there is no vortex visible in the wind fields. In the case of the WPEs, we conclude that the Alpine inflow takes place at the southern or ~~south-eastern~~ southeastern side of the Alps, which is supported by the mostly ~~southernly~~ southerly located precipitation amounts. These features are similar to the "Canarian Trough" described by Stucki et al. (2012) in association with past extreme floods in Switzerland. These cyclones are strongly influenced by a low over Brittany and thus show a southwesterly flow (Stucki et al., 2012). The same is true for the WPEs, which are strongly influenced by a low in the northeast of their cyclone centres. Additionally it must be kept in mind that cyclone development in the vicinity of the Alps is a very complex problem. Due to strong non-geostrophic secondary flows, the appearance of near-surface closed isobars is not sufficient to produce cyclonic vorticity (Speranza, 1975) . Thus, although WPE can be detected as closed isobars, i.e. cyclones, these cyclones are shallow and show no real meteorological impact, which stands in clear contrast to the cyclones associated with HPE.

The fact that unlike humidity, the large-scale dynamic behaviour of the atmosphere allows a clear differentiation between the HPEs and WPEs, leads us to the conclusion that the thermodynamic state of the atmosphere only plays a secondary role in triggering heavy precipitation associated to Vb-events. These findings have important implications for a future climate change. On the one hand, an increased moisture amount is projected in the atmosphere as response to the increase in temperature with a changing climate (again associated to the Clausius-Claperyon equation). Hence, an increase in precipitation amounts can be expected in principle in the future. This argument is supported by

Zappa et al. (2014) stating, that an increase in atmospheric moisture content is responsible for an increased cyclone precipitation intensity in the northern Mediterranean. On the other hand, Pal et al. (2004), Yin (2005), Giorgi and Lionello (2008) and Raible et al. (2010) argue that shifts in the cyclone track, and thus changes in the more important dynamical part of a Vb-cyclone, are expected under a future climate. In particular, the former studies project a poleward shift of the storm track in a future climate, while Woollings et al. (2012) expect an eastward extension of the storm track towards Europe. These projections about the changing behaviour of the storm track in the future suggests that the phenomenon Vb-cyclone could become even rarer if either of the two shifts occur. Combining these two arguments, it can be expected that Vb-cyclones would happen more seldom, but with an increased intensity in precipitation. Nissen et al. (2013) confirmed this in point in the same direction in a study on Vb-cyclones. However, this hypothesis is associated with a large amount of uncertainty, and a more precise assessment of the future behaviour of Vb-events and their related impacts cannot be done with the evidence exposed in this analysis. Thus, more research on the large-scale dynamic changes of different Vb-cyclone subcategories under a future climate is needed to fully understand the changes in precipitation amounts and frequency of Vb-cyclones.

Even though it is possible to find a reason for the high variability in Vb-cyclone triggered precipitation amounts, the exact triggering mechanism for precipitation cannot be found using the coarse resolution of ERA-Interim. This is especially true in the Alps Alpine region, where the coarse resolution is a strong limiting factor of ERA-Interim. As the Vb-cyclones are phenomena, which strongly depend on mountains, more insights could be gained using regional modelling. Dynamical downscaling will not only improve the spatial resolution, but also the temporal resolution. Such higher resolved dataset will allow a closer look into thermodynamics, while an increased temporal resolution can provide additional information on dynamics (Muskulus and Jacob, 2005). Planned sensitivity studies on SST over different locations and soil moisture in the regional model framework will allow to gain deeper insight on the moisture source and thus on thermodynamics in several single Vb-events. Furthermore, the fine resolution allows distinguishing the mechanisms that trigger a Vb-cyclone with and without meteorological impact. Additionally the regional model framework can simulate the diabatic heating processes and thus PV development or the presence of warm conveyor belts during the cyclones lifecycle. Thus, future studies will consider the re-evaluation of the Vb-cyclone climatology based on high-regional downscaling products, as well as direct assessments of the evolution Vb-events through climate simulations.

References

530 Bengtsson, L., Hodges, K. I., Esch, M., Keenlyside, N., Kornblueh, L., Luo, J.-J., and Yamagata, T.: How may tropical cyclones change in a warmer climate?, Tellus A, 59, 539–561, doi:10.1111/j.1600-0870.2007.00251.x, 2007.

Beniston, M.: August 2005 intense rainfall event in Switzerland: Not necessarily an analog for strong convective events in a greenhouse climate, Geophysical Research Letters, 33, doi:10.1029/2005GL025573, 2006.

535 Blender, R., Fraedrich, K., and Lunkeit, F.: Identification of cyclone-track regimes in the North Atlantic, Quarterly Journal of the Royal Meteorological Society, 123, 727–741, doi:10.1002/qj.49712353910, 1997.

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A. C. M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A. J., Haimberger, L., Healy, S. B., Hersbach, H., Hólm, E. V.,

540 Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A. P., Monge-Sanz, B. M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thëpaut, J.-N., and Vitart, F.: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system, Quarterly Journal of the Royal Meteorological Society, 137, 553–597, doi:10.1002/qj.828, 2011.

Donat, M. G., Pardowitz, T., Leckebusch, G. C., Ulbrich, U., and Burghoff, O.: High-resolution refinement of a

545 storm loss model and estimation of return periods of loss-intensive storms over Germany, Nat. Hazards Earth Syst. Sci., 11, 2821–2833, doi:10.5194/nhess-11-2821-2011, 2011.

Fink, A. H., Pohle, S., Pinto, J. G., and Knippertz, P.: Diagnosing the influence of diabatic processes on the explosive deepening of extratropical cyclones, Geophysical Research Letters, 39, L07 803, doi:10.1029/2012GL051025, 2012.

550 Fricke, W. and Kaminski, U.: Ist die Zunahme von Starkniederschlägen auf veränderte Wetterlagen zurückzuführen, GAW Brief des Deutschen Wetterdienstes, 12, 2002.

Gao, X., Pal, J. S., and Giorgi, F.: Projected changes in mean and extreme precipitation over the Mediterranean region from a high resolution double nested RCM simulation, Geophysical Research Letters, 33, L03 706, doi:10.1029/2005GL024954, 2006.

555 Giorgi, F.: Climate change hot-spots, Geophysical Research Letters, 33, L08 707, doi:10.1029/2006GL025734, 2006.

Giorgi, F. and Lionello, P.: Climate change projections for the Mediterranean region, Global and Planetary Change, 63, 90–104, doi:10.1016/j.gloplacha.2007.09.005, 2008.

Grams, C. M., Binder, H., Pfahl, S., Piaget, N., and Wernli, H.: Atmospheric processes triggering the central

560 European floods in June 2013, Nat. Hazards Earth Syst. Sci., 14, 1691–1702, doi:10.5194/nhess-14-1691-2014, 2014.

Grazzini, F. and van der Grijn, G.: Central European floods during summer 2002, ECMWF Newsletter, 96, 2002.

Gómez-Navarro, J. J., Montávez, J. P., Jerez, S., Jiménez-Guerrero, P., and Zorita, E.: What is the role of the

565 observational dataset in the evaluation and scoring of climate models?, Geophysical Research Letters, 39, L24 701, doi:10.1029/2012GL054206, 2012.

17

Haylock, M. R., Hofstra, N., Klein Tank, A. M. G., Klok, E. J., Jones, P. D., and New, M.: A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006, Journal of Geophysical Research: Atmospheres, 113, D20 119, doi:10.1029/2008JD010201, 2008.

570 Held, H., Gerstengarbe, F.-W., Pardowitz, T., Pinto, J. G., Ulbrich, U., Born, K., Donat, M. G., Karremann, M. K., Leckebusch, G. C., Ludwig, P., Nissen, K. M., Österle, H., Prahl, B. F., Werner, P. C., Befort, D. J., and Burghoff, O.: Projections of global warming-induced impacts on winter storm losses in the German private household sector, Climatic Change, 121, 195–207, doi:10.1007/s10584-013-0872-7, 2013.

Hofstätter, M. and Chimani, B.: Van Bebber's cyclone tracks at 700 hPa in the Eastern Alps for
575 1961–2002 and their comparison to circulation type classifications, Meteorologische Zeitschrift, 21, 459–473, doi:10.1127/0941-2948/2012/0473, 2012.

Hofstra, N., Haylock, M., New, M., and Jones, P. D.: Testing E-OBS European high-resolution gridded data set of daily precipitation and surface temperature, Journal of Geophysical Research: Atmospheres, 114, D21 101, doi:10.1029/2009JD011799, 2009.

580 IPCC-AR4: The physical science basis. In: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2007.

IPCC-SREX: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A
585 Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change [Field, C.B., V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley (eds.)]., Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2012.

James, P., Stohl, A., Spichtinger, N., Eckhardt, S., and Forster, C.: Climatological aspects of the extreme Eu-
590 ropean rainfall of August 2002 and a trajectory method for estimating the associated evaporative source regions, Nat. Hazards Earth Syst. Sci., 4, 733–746, doi:10.5194/nhess-4-733-2004, 2004.

Kaspar, M. and Müller, M.: Selection of historic heavy large-scale rainfall events in the Czech Republic, Nat. Hazards Earth Syst. Sci., 8, 1359–1367, doi:10.5194/nhess-8-1359-2008, 2008.

Köppen, W.: Die Zugstrassen der barometrischen Minima in Europa und auf dem nordatlantischen Ocean und
595 ihr Einfluss auf Wind und Wetter bei uns, Mittheilungen der Geographischen Gesellschaft in Hamburg, 1, 76–97, 1881.

Kron, W., Steuer, M., Löw, P., and Wirtz, A.: How to deal properly with a natural catastrophe database – analysis of flood losses, Nat. Hazards Earth Syst. Sci., 12, 535–550, doi:10.5194/nhess-12-535-2012, 2012.

Kundzewicz, Z. W., Ulbrich, U., Brücher, T., Graczyk, D., Krüger, A., Leckebusch, G. C., Menzel, L., Pińskwar,
600 I., Radziejewski, M., and Szwed, M.: Summer Floods in Central Europe – Climate Change Track?, Natural Hazards, 36, 165–189, doi:10.1007/s11069-004-4547-6, 2005.

Lionello, P., Dalan, F., and Elvini, E.: Cyclones in the Mediterranean region: the present and the doubled CO2 climate scenarios, Climate Research, 22, 147–159, doi:10.3354/cr022147, 2002.

Lionello, P., Trigo, I. F., Gil, V., Liberato, M. L. R., Nissen, K., Pinto, J. G., Raible, C. C., Reale, M., Tanzarella,
605 A., Trigo, R. M., Ulbrich, S., and Ulbrich, U.: Objective Climatology of Cyclones in the Mediterranean

Region: a consensus view among methods with different system identification and tracking criteria, Tellus, in preparation.

Martius, O., Zenklusen, E., Schwierz, C., and Davies, H. C.: Episodes of alpine heavy precipitation with an overlying elongated stratospheric intrusion: a climatology, International Journal of Climatology, 26, 1149–1164, doi:10.1002/joc.1295, 2006.

Mudelsee, M., Börngen, M., Tetzlaff, G., and Grünewald, U.: Extreme floods in Central Europe over the past 500 years: Role of cyclone pathway „Zugstrasse Vb", Journal of Geophysical Research: Atmospheres, 109, D23 101, doi:10.1029/2004JD005034, 2004.

Muskulus, M. and Jacob, D.: Tracking cyclones in regional model data: The future of Mediterranean storms, Adv. Geosci., 2, 13–19, doi:10.5194/adgeo-2-13-2005, 2005.

Neu, U., Akperov, M. G., Bellenbaum, N., Benestad, R., Blender, R., Caballero, R., Cocozza, A., Dacre, H. F., Feng, Y., Fraedrich, K., Grieger, J., Gulev, S., Hanley, J., Hewson, T., Inatsu, M., Keay, K., Kew, S. F., Kindem, I., Leckebusch, G. C., Liberato, M. L. R., Lionello, P., Mokhov, I. I., Pinto, J. G., Raible, C. C., Reale, M., Rudeva, I., Schuster, M., Simmonds, I., Sinclair, M., Sprenger, M., Tilinina, N. D., Trigo, I. F., Ulbrich, S., Ulbrich, U., Wang, X. L., and Wernli, H.: IMILAST: A community effort to intercompare extratropical cyclone detection and tracking algorithms, Bulletin of the American Meteorological Society, 94, 529–547, doi:10.1175/BAMS-D-11-00154.1, 2013.

Nissen, K. M., Ulbrich, U., and Leckebusch, G. C.: Vb cyclones and associated rainfall extremes over Central Europe under present day and climate change conditions, Meteorologische Zeitschrift, 22, 649–660, doi:10.1127/0941-2948/2013/0514, 2013.

Nissen, K. M., Leckebusch, G. C., Pinto, J. G., and Ulbrich, U.: Mediterranean cyclones and windstorms in a changing climate, Regional Environmental Change, 14, 1873–1890, doi:10.1007/s10113-012-0400-8, 2014.

Pal, J. S., Giorgi, F., and Bi, X.: Consistency of recent European summer precipitation trends and extremes with future regional climate projections, Geophysical Research Letters, 31, L13 202, doi:10.1029/2004GL019836, 2004.

Pinto, J. G., Spangehl, T., Ulbrich, U., and Speth, P.: Assessment of winter cyclone activity in a transient ECHAM4-OPYC3 GHG experiment, Meteorologische Zeitschrift, 15, 279–291, doi:10.1127/0941-2948/2006/0128, 2006.

Pinto, J. G., Ulbrich, S., Parodi, A., Rudari, R., Boni, G., and Ulbrich, U.: Identification and ranking of extraordinary rainfall events over Northwest Italy: The role of Atlantic moisture, Journal of Geophysical Research: Atmospheres, 118, 2085–2097, doi:10.1002/jgrd.50179, 2013.

Raible, C. C.: On the relation between extremes of midlatitude cyclones and the atmospheric circulation using ERA40, Geophysical Research Letters, 34, L07 703, doi:10.1029/2006GL029084, 2007.

Raible, C. C., Della-Marta, P. M., Schwierz, C., Wernli, H., and Blender, R.: Northern Hemisphere extratropical cyclones: A comparison of detection and tracking methods and different reanalyses, Monthly Weather Review, 136, 880–897, doi:10.1175/2007MWR2143.1, 2008.

Raible, C. C., Ziv, B., Saaroni, H., and Wild, M.: Winter synoptic-scale variability over the Mediterranean Basin under future climate conditions as simulated by the ECHAM5, Climate Dynamics, 35, 473–488, doi:10.1007/s00382-009-0678-5, 2010.

19

645 Sodemann, H. and Zubler, E.: Seasonal and inter-annual variability of the moisture sources for Alpine precipitation during 1995–2002, International Journal of Climatology, 30, 947–961, doi:10.1002/joc.1932, 2010.

Sodemann, H., Wernli, H., and Schwierz, C.: Sources of water vapour contributing to the Elbe flood in August 2002—A tagging study in a mesoscale model, Quarterly Journal of the Royal Meteorological Society, 135, 205–223, doi:10.1002/qj.374, 2009.

650 Speranza, A.: The formation of baric depressions near the Alps, Annals of Geophysics, 28, 177–217, doi:10.4401/ag-4898, 1975.

Stohl, A. and James, P.: A Lagrangian analysis of the atmospheric branch of the global water cycle. Part I: Method description, validation, and demonstration for the August 2002 flooding in Central Europe, Journal of Hydrometeorology, 5, 656–678, doi:10.1175/1525-7541(2004)005<0656:ALAOTA>2.0.CO;2, 2004.

655 Stucki, P., Rickli, R., Brönnimann, S., Martius, O., Wanner, H., Grebner, D., and Luterbacher, J.: Weather patterns and hydro-climatological precursors of extreme floods in Switzerland since 1868, Meteorologische Zeitschrift, 21, 531–550, doi:10.1127/0941-2948/2012/368, 2012.

Stucki, P., Brönnimann, S., Martius, O., Welker, C., Imhof, M., von Wattenwyl, N., and Philipp, N.: A catalog of high-impact windstorms in Switzerland since 1859, Nat. Hazards Earth Syst. Sci., 14, 2867–2882,
660 doi:10.5194/nhess-14-2867-2014, 2014.

Trigo, I. F., Davies, T. D., and Bigg, G. R.: Objective climatology of cyclones in the Mediterranean region, Journal of Climate, 12, 1685–1696, doi:10.1175/1520-0442(1999)012<1685:OCOCIT>2.0.CO;2, 1999.

Ulbrich, U., Brücher, T., Fink, A. H., Leckebusch, G. C., Krüger, A., and Pinto, J. G.: The central European floods of August 2002: Part 1 – Rainfall periods and flood development, Weather, 58, 371–377,
665 doi:10.1256/wea.61.03A, 2003a.

Ulbrich, U., Brücher, T., Fink, A. H., Leckebusch, G. C., Krüger, A., and Pinto, J. G.: The central European floods of August 2002: Part 2 –Synoptic causes and considerations with respect to climatic change, Weather, 58, 434–442, doi:10.1256/wea.61.03B, 2003b.

Van Bebber, W.: Die Zugstrassen der barometrischen Minima nach den Bahnenkarten der deutschen Seewarte
670 für den Zeitraum 1875-1890, Meteorologische Zeitschrift.[Offprint], 8, 361–366, 1891.

Winschall, A., Pfahl, S., Sodemann, H., and Wernli, H.: Impact of North Atlantic evaporation hot spots on southern Alpine heavy precipitation events, Quarterly Journal of the Royal Meteorological Society, 138, 1245–1258, doi:10.1002/qj.987, 2012.

Woollings, T., Gregory, J. M., Pinto, J. G., Reyers, M., and Brayshaw, D. J.: Response of the North At-
675 lantic storm track to climate change shaped by ocean-atmosphere coupling, Nature Geoscience, 5, 313–317, doi:10.1038/ngeo1438, 2012.

Yin, J. H.: A consistent poleward shift of the storm tracks in simulations of 21st century climate, Geophysical Research Letters, 32, L18 701, doi:10.1029/2005GL023684, 2005.

Zängl, G.: Numerical simulations of the 12-13 August 2002 flooding event in eastern Germany, Quarterly
680 Journal of the Royal Meteorological Society, 130, 1921–1940, doi:10.1256/qj.03.152, 2004.

Zappa, G., Hawcroft, M. K., Shaffrey, L., Black, E., and Brayshaw, D. J.: Extratropical cyclones and the projected decline of winter Mediterranean precipitation in the CMIP5 models, Climate Dynamics, pp. 1–12, doi:10.1007/s00382-014-2426-8, 2014.
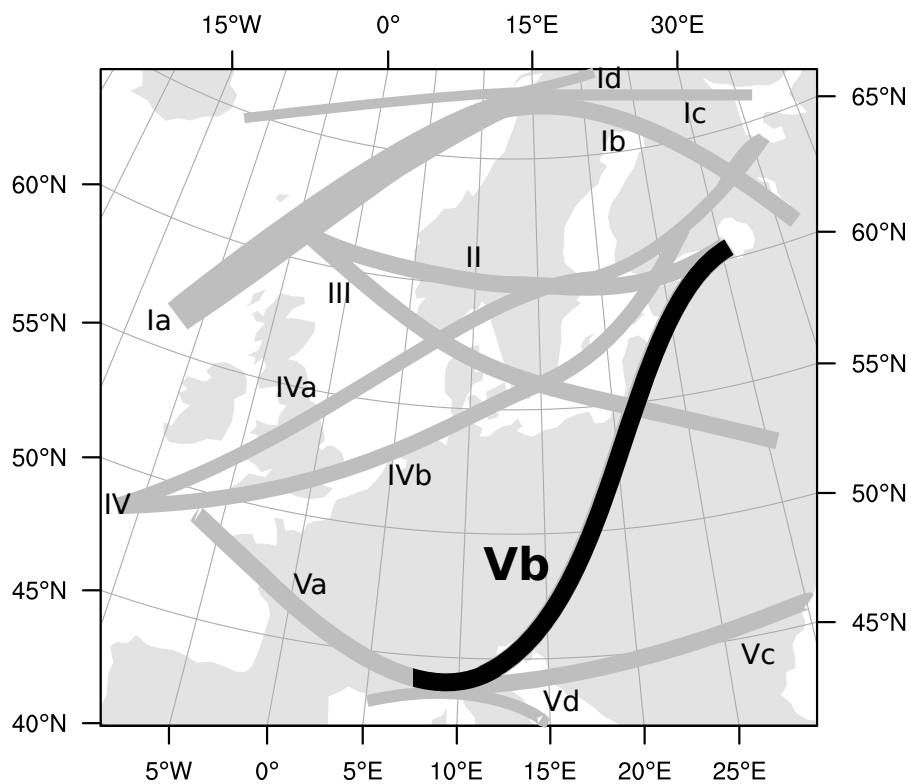
Figure 1. Trajectories of the barometric minima between 1876 – 1880, as defined by W.J. van Bebber in 1981. The trajectory that defines Vb-cyclones is highlighted in black.
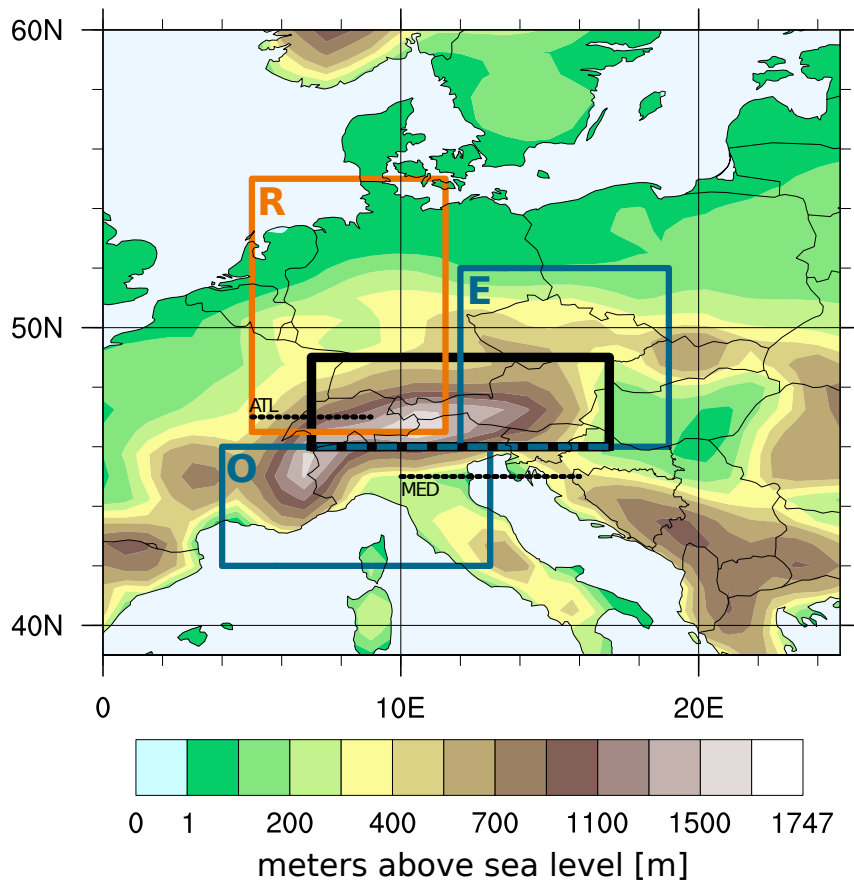
Figure 2. The three boxes used to automatically filter out the Vb-cyclones from the total number of cyclones found by the tracking technique (Blender et al., 1997). O, E and R denote the origin, the end and the restriction box, respectively. The black box over the alpine region defines the area of interest for precipitation amounts. The two stippled black lines indicate the position of the two cross-sections used to calculate the moisture flux. The topography corresponds to the one implemented in ERA-Interim.
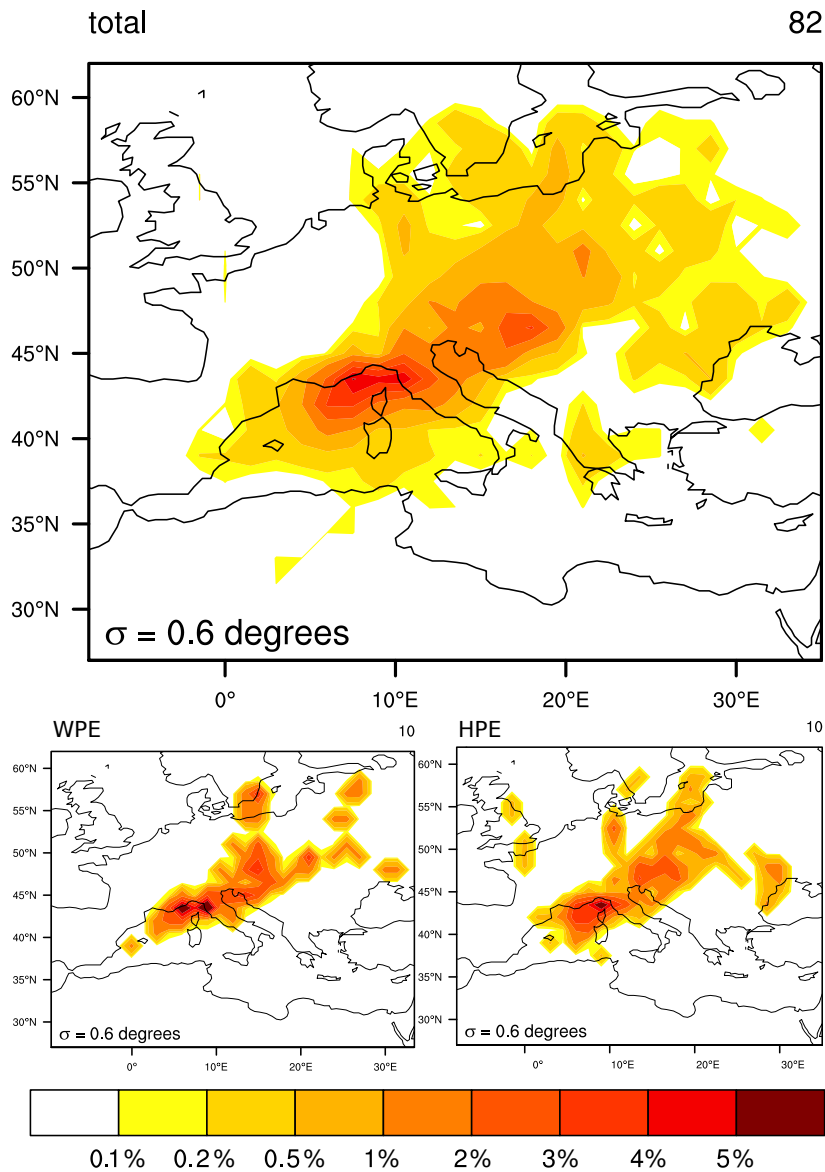
Figure 3. Probability density field of all detected Vb-cyclone ~~centers~~ centres (top panel), of the heavy precipitation events (HPEs) (bottom left panel) and of the weak precipitation events (WPEs) (bottom right panel). The shading shows how probable it is that a Vb-cyclone centre is located at the according grid point at any time step in the 1979-2013 period.
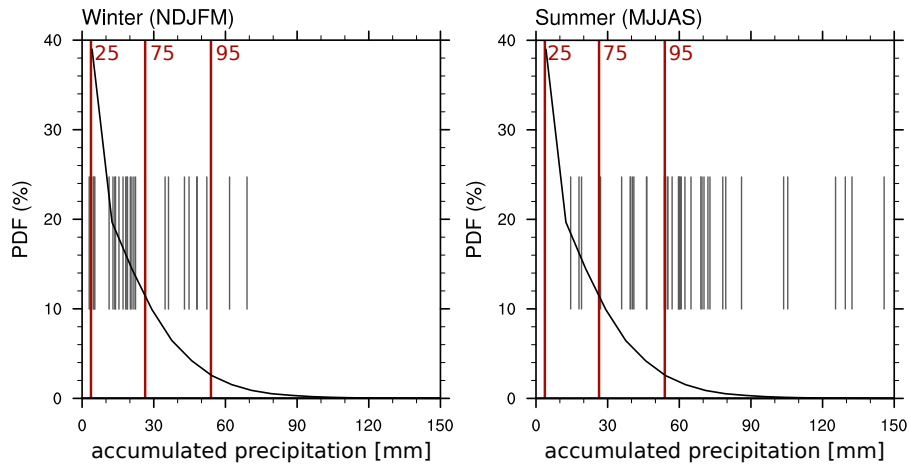
Figure 4. Probability density function of the accumulated precipitation from ERA-Interim of Vb-events (black line) for extended winter (left panel) and extended summer (right panel). The red lines indicate the 25, 75 and 95 percentile from left to right. The vertical, black lines indicate the accumulated precipitation of all Vb-cyclones occurring during each season, respectively.
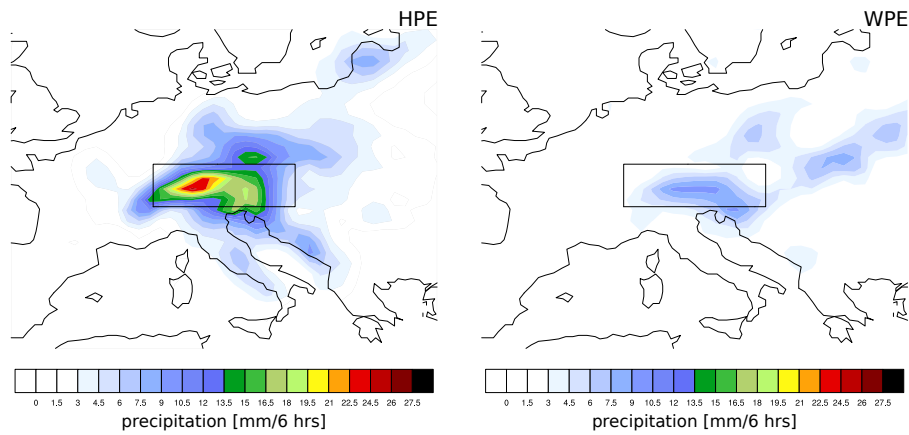
Figure 5. Average precipitation during the time step with maximum precipitation for the 10 HPEs (left panel) and the 10 WPEs (right panel). The black box indicates the precipitation region of interest, depicted also in Fig. 2 as black rectangle.
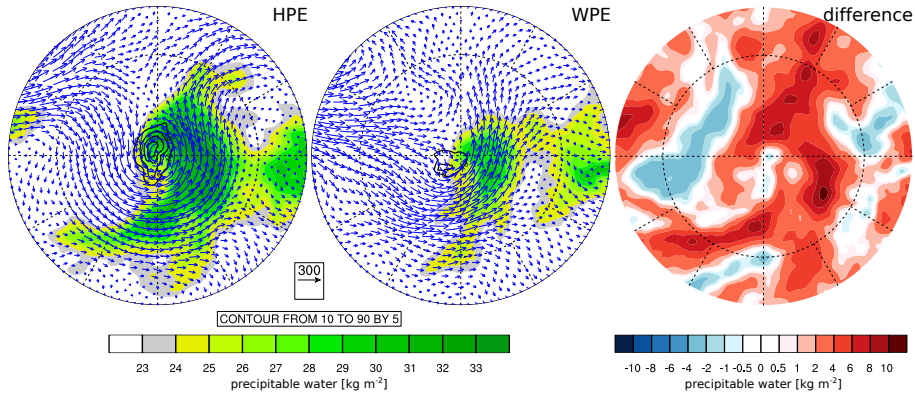
Figure 6. Composites of precipitable water content [~~kg/kg~~kg m^{-2}, shading] and precipitation amounts (black contours) for the HPEs (left panel) and for the WPEs (centre panel). Additionally the moisture flux is shown by arrows integrated over the vertical structure of the atmosphere (reference vector: 300~~kgm/kgs~~ kg m^{-1} s^{-1}). The time step with maximum precipitation is shown for all variables. The distance from the centre of the composite cyclone to the edge is 23°. The differences in precipitable water between HPEs and WPEs is shown (right panel).
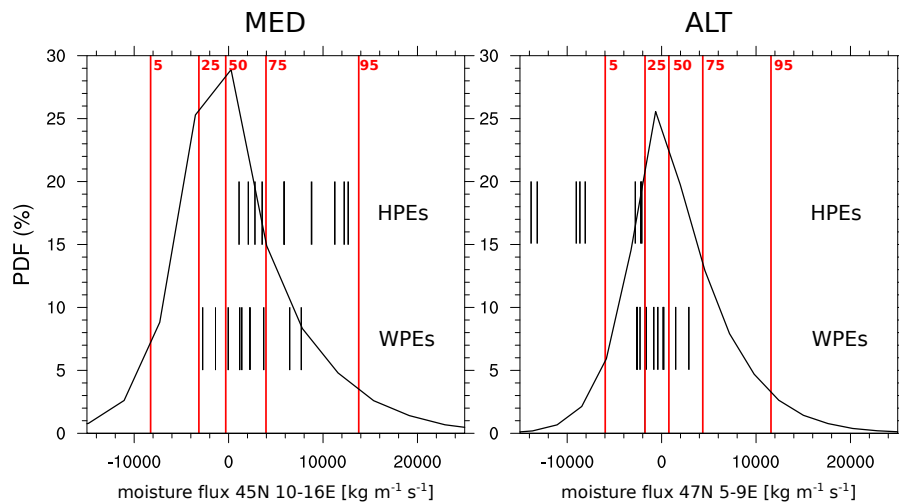
Figure 7. Probability density function of the accumulated moisture flux of all Vb-events (black line). The vertical top (bottom) lines indicate the accumulated moisture flux of the HPEs (WPEs) through the stippled black lines depicted in Fig. 2 labelled with "MED" (left panel) and labelled with "ATL" (right panel). The red lines indicate the 5, 25, 50, 75 and 95 percentile from left to right.
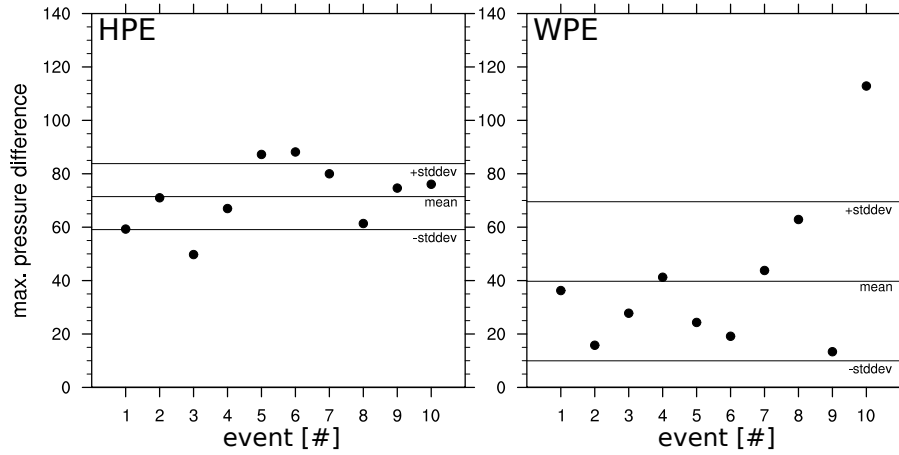
Figure 8. Difference between the minimum and maximum pressure during the entire life cycle for the HPEs (left panel) and WPEs (right panel). The events are sorted according to precipitation produced in the target area (Fig. 2), with #1 being the most extreme precipitation event. The three horizontal black lines indicate the mean and the standard deviation, respectively.
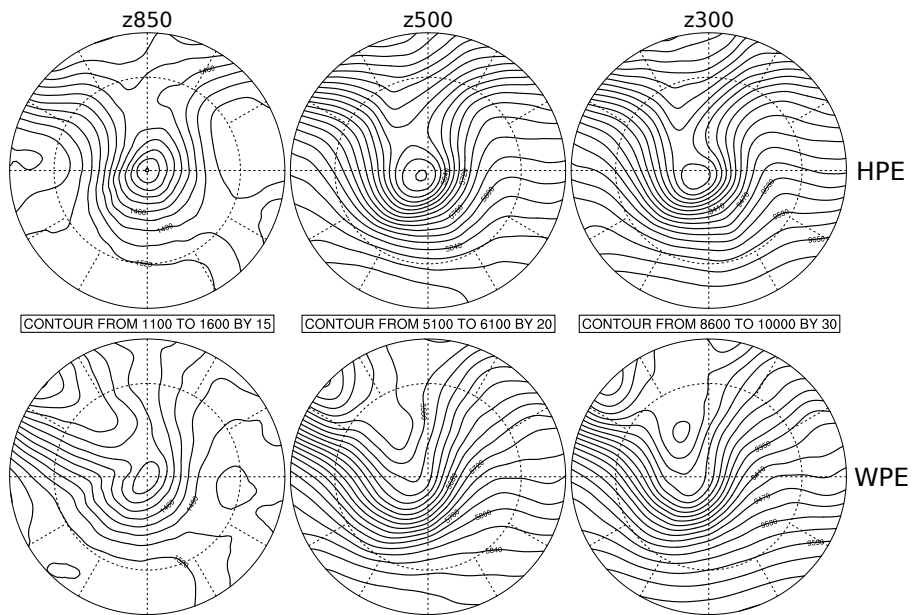

Figure 9. Average geopotential height at 850 hPa (left column), 500 hPa (centre column) and 300 hPa (right column) for the time step with maximum precipitation of all HPEs (upper row) and WPEs (bottom row). The distance from the centre of the composite cyclone to the edge is 23°.
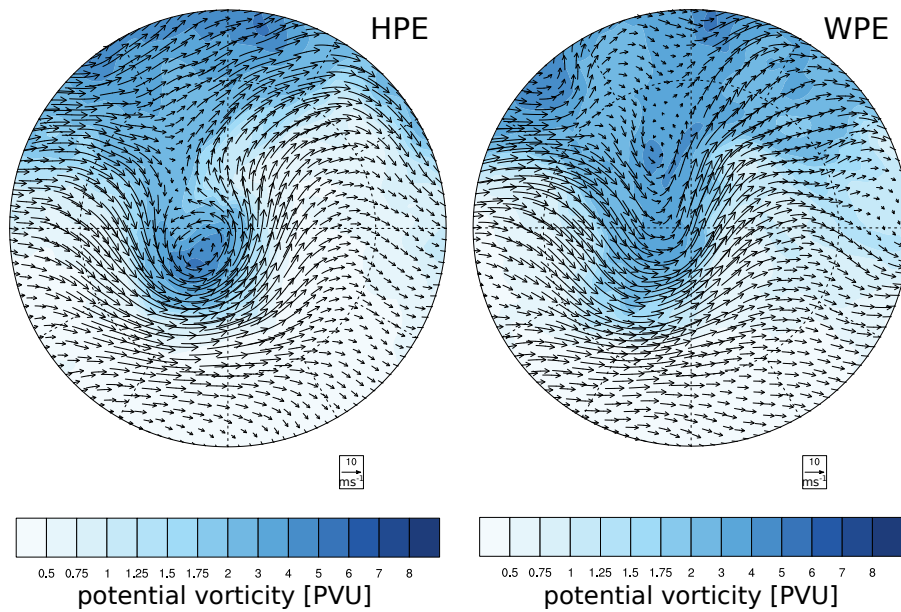
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Figure 10. Composites of potential vorticity [PVU, shading] on the 325 K potential temperature surface at the time step with maximum precipitation of the HPEs (left panel) and the WPEs (right panel). Wind fields are also shown for the 325 K potential temperature surface (reference vector: 10~~m/s~~ $\mathrm{m\,s^{-1}}$). The distance from the centre of the composite cyclone to the edge is $23°$.