Response to comments of Anonymous Reviewer #2

I like to thank the Referee for her/his constructive comments that help me to improve the manuscript. Below, detailed responses to all comments are given.

1. If I understand well, reading section 2, the author calculates the blocking/cyclone frequencies during the intra-daily weather extremes. However, the paper aims to interpret the blocking/cyclone frequencies composite maps in terms of remote effects of these features on weather extremes. So, I was wondering whether the temporal coherence is important (i.e blocking/cyclones features before the weather extreme events). Indeed, summer hot (resp. winter cold) extremes can be induced in Europe by specific advected atmospheric circulations and accumulation of sensible heat flux through several days in lower layers of troposphere due to combined depleted soil-moisture and persistent blocking for example (resp. gradual reduction of heat fluxes due to high snow cover and persistent blocking for example). Calculating frequency of blocking/cyclone only during the occurrence of the weather extremes can make more complex the causal relationship claimed by the author. This leads me to my second remark.

The remote effects of cyclones and blocking on weather extremes referred to in the manuscript are primarily not associated with the movement of the circulation feature itself, but are linked to its anomalous wind field, which extends also beyond the area directly associated with the cyclone or blocking (a note on this will be added to the introduction). For instance, the cyclonic circulation linked to a cyclone (which can extend far away from the cyclone centre) can lead to the transport of moist air towards a mountain ridge and thus to heavy precipitation, as described in section 3.1. As such remote effects are quasi-instantaneous (assuming that the synoptic-scale wind field is close to geostrophic balance), they can be readily assessed with the help of temporally coherent frequency anomalies.

Of course, time-lagged analyses as suggested by the Reviewer can provide additional insights. As two examples, the Figure below shows time-lagged blocking anomalies associated with cold extremes as well as time lagged cyclone anomalies linked to precipitation extremes in France. While the blocking anomaly is temporally very persistent and even larger 3 days before than during the events, the cyclone anomaly 3 days before the precipitation extremes is weaker and shifted to the west, indicating the typical eastward trajectory of cyclones in this region. A weakening of the time-lagged anomaly pattern going backwards in time can reflect, among other things, the limited life time of the circulation features or a large variability in their trajectories. Since the time-lagged anomaly patterns show much variability with respect to the type of extreme event, circulation feature and target location, a systematic assessment would be required. However, this would lead to 6-10 more figures, which in my opinion is far too much to be included in the present manuscript (which already describes the spatial variability as well as the differences between different types of extremes in a systematic way). I will thus extend the conclusion section as follows: 'Furthermore, the present analysis should be extended to capture also the time-lagged relation between circulation features and extreme events. This can yield novel insights, e.g. on the persistence of the anomalies and on typical feature trajectories. It can also help to assess potential benefits for medium-range weather forecasts of extreme events. The relationship to cyclones and blocking may be useful in this field, since these synoptic-scale circulation features are typically embedded in larger-scale Rossby waves, which may have upstream precursors far ahead of the event (e.g. Sisson and Gyakum, 2004; Grazzini, 2007; Martius et al., 2008).'

Regarding the causal relationship between circulation features and extreme events, which is also mentioned by the Reviewer: I think this is very clear for precipitation and wind extremes, for which the role of cyclones has been investigated in various case studies. Nevertheless, also for temperature extremes the present reasoning is consistent with a recent, more process-oriented study (Bieli et al., Q. J. Roy. Meteor. Soc., doi:10.1002/qj.2339, in press) and also not inconsistent with other previous studies, as detailed in the reply to comment 2.

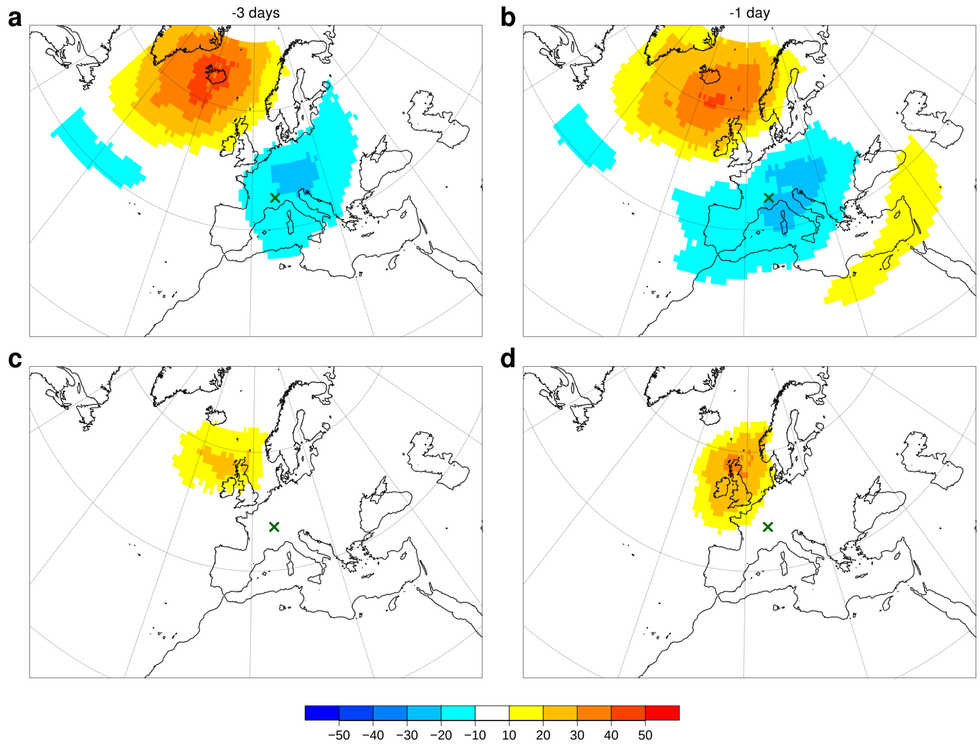

Figure 1: (a,b) Time-lagged conditional blocking frequency anomalies $\tilde{f}_{\mathrm{b}}$ for cold temperature extremes at 6° E, 45° N. (c,d) Time-lagged conditional cyclone frequency anomalies $\tilde{f}_{\mathrm{c}}$ for precipitation extremes at 6° E, 47° N. The frequency anomalies 3 days before the extreme events are shown in (a,c), the anomalies 1 day before the events in (b,d).

2. The author interprets the colocation of cyclone/blocking frequency center with hot extremes as a fingerprint of low/no advection and preferential adiabatic heating mechanism. I think this point is incorrect. Indeed, various authors have reported that in Western Europe, a South-North propagation of heat continental anomalies is coherently observed (e.g Vautard et al., 2007 ; Zampieri et al., 2009 ; Quesada et al., 2012). In another words, advection could be a dominant forcing of european hot extremes occurrence! Moreover, european temperature variability in summer is less dependant of large-scale atmospheric dynamics compared to winter (e.g Cassou et al., 2005 ; Cattiaux et al., 2010). So, my point of view is that blocking frequency is a limited metric to get the full picture: blocking can be inefficient in temperature in-

crease in some regions (e.g wet Northern regions) and very efficient to trigger feedback amplifications (e.g southern Spain) leading to hot extremes. For example, a blocking event in Southern Europe can have temperature impacts on Northern Europe some days or weeks after, which seems in contradiction with what the author claims in Section 3.3. Therefore, to better explain the temperature extremes occurrence and remote effects, one should take into account: blocking frequency but also soil-state (e.g winter snow or summer soil-moisture) and strength of blocking. How does the authors study fit with previous papers and the above-mentionned considerations?

I do not think that the present results are inconsistent with the previous studies on European heat waves mentioned by the Reviewer. The main difference is the time scale on which processes are analysed: While these previous studies looked at monthly to seasonal time scales (on which the northward propagation of an anomaly signal was found), I focus on the synoptic-scale processes during the days around the peak heat anomalies, which provides a complementary perspective. The conclusion that there is no substantial southerly advection during these days is substantiated by the trajectory calculations of Bieli et al. (Q. J. Roy. Meteor. Soc., doi:10.1002/qj.2339, in press). The following paragraph will be added to section 3.3 to make this clearer: 'Furthermore, the present results complement other studies on European heat waves that mainly focused on processes on monthly and seasonal time scales and showed that dry conditions in spring favour the occurrence of hot summers (Fischer et al., 2007; Vautard et al., 2007; Zampieri et al., 2009; Quesada et al., 2012). In particular, rainfall deficits over Southern Europe have been shown to precede summer heat waves also in more northerly regions, indicating a northward propagation of the anomaly signal (Vautard et al., 2007; Zampieri et al., 2009). The results presented in this manuscript suggest that this propagation does not happen directly via the transport of warm air masses during the peaks of the heat waves (which correspond to six-hourly hot extremes as defined here), as there is no substantial southerly advection in the prevailing blocking conditions, but rather before the maximum temperatures are reached.'

Note that the linkage between blocking and hot temperature extremes is really stronger over northern than over southern Europe, as also shown in a previous study (Pfahl and Wernli, 2012c). In this previous paper, we also investigated the effects of strong and weak blocking.

Finally, I do not want to claim that blocking frequency was the only important factor influencing the occurrence of summer heat extremes. In general, the cyclone and blocking anomalies found here are often necessary, but not sufficient requirements for the occurrence of weather extremes, and other processes are of course important in addition (see also the reply to comment 1 of Reviewer 1). A remark on this issue will be added to the conclusions section.

3. The author points out that "(...) the magnitude of the extreme events (...) may be underestimated in ERA-Interim compared to point measurements" but all variables are interpolated at 1 degree resolution. As far as I know, ERA-Interim provides data also at 0.75 degrees resolution. So, could the resolution have an impact on blocking/cyclone features (or e.g on mountainous areas) presented here? Are the results robust with ERA-Interim finer resolution?

Originally, the ERA-Interim data have a spectral resolution of T255, which corresponds to a grid spacing of about 0.75 degrees in a geographical grid,this is correct. Interpolating the data to a 0.75 instead of 1 degree grid may lead to slightly larger precipitation amounts locally, but hardly effects the identification of extreme events in the present study, since the exact magnitude of the events is not important here. It is only the timing of the extreme events that is used for the composite analysis, and this timing is inherent in the original data set. Also with respect to the cyclone and blocking identification, I have not explicitly tested a resolution of 0.75 degrees (this would require to download and reprocess the whole data set, which is a huge computational effort), but it is again unlikely that this would have a notable effect. Both blocking and cyclones are relatively large-scale features, and the synoptic-scale circulation is hardly effected by the exact interpolation procedure. The slightly higher resolution may lead to small variations in specific SLP contours near topography, but again this does not have a large influence on the present composite analysis.

4. p1872, The choice of intra-daily (i.e six-hourly) seems arbitrary. For temperature extremes, why did the author not choose daily or multi-daily (waves) indices? The intra-daily indices are more punctual and could be a priori more related to local causes.

The focus of this study is on extreme events and the associated mechanisms on short, sub-daily to daily time scales (a note on this will be added to the introduction), providing complementary information compared to previous investigations focusing on longer temporal scales, in particular for temperature extremes, as outlined in the response to comment 2. Different types of extremes are investigated with a common methodology and thus defined for a common period. The advantage of looking at six-hourly extremes is that very coherent synoptic-scale circulation anomalies can be detected. If longer time scales are considered, a considerable part of the synoptic-scale signal is smoothed out, since e.g. cyclones can move over considerable distances during one or more days. Note that the six-hourly hot temperature extremes correspond also to the peaks of longer-lasting heat wave (e.g. in summer 2003). Finally, the results from this study show that also for such six-hourly extremes, very coherent and significant large-scale circulation anomalies can be detected.