Linking ENSO and heavy rainfall events over Coastal British Columbia through a weather pattern classification

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Answer to the reviewer comments

Suggestions made by the two reviewers are gratefully acknowledged. We modified the text in response to the main criticisms.
In the following, we list all the reviewers' comments (in *italic and blue*) and we provide specific responses to these comments (in black) and the modifications brought to the manuscript (in *italic and black*).

1 REVIEWER 2

1.1 General comments and recommendation

The manuscript presents the interest of a weather pattern classification to improve our understanding of rainfall characterization at regional scale. Heavy rainfall is the specific target. The manuscript aims at identifying the relationship between ENSO oscillations, weather patterns and heavy rainfall statistics in the coastal region of British Columbia. This subject is of a particular interest when considering the general context of climate evolution and its impact at regional scale. Understanding the actual regional climate, in particular the link between atmospheric circulations, ocean forcing and rainfall in a given region, will aim at building a robust method to study the evolution of the rainfall regime and/or the occurrence of heavy precipitation in the future scenarios. Therefore, the present study addresses relevant scientific questions that are within the scope of HESS.
Nevertheless, the paper is difficult to read and understand. Concepts are not fully presented. For example, the description of the methodology to provide weather classification needs to be improved, in particular its evaluation is missing. The quality of the Figures is sometime very poor and makes the understanding difficult. It therefore needs major modifications to reach HESS standard.

1.2 Major/Minor comments

1.2.1 1/ Introduction

Weather clustering is widely used in particular for rainfall issues. The authors should better highlight the interest / limit of their approach to other methods (e.g. Kohonen approach (e.g. work of Michaelides ; …); Statisto-dynamical approach (e.g. work of Beaulant et al. ; …); Statistical downscaling (e.g. work of Boé et al. ; Hingray et al. ; …) ; etc …).

We agree with the reviewer that we presented neither the different existing weather pattern classification methods nor the interest and limits of our approach. This choice was intentional, since the goal of the paper is not to present a new weather pattern classification method but is to apply an existing methodology which has been already applied in two different contexts (application to France in Garavaglia et al. 2010 and 2011, and application to Austria in Brigode et al. 2012), and to study the link between heavy rainfall events over Coastal BC and ENSO through a weather pattern classification. Nevertheless, we agree that it is needed to clearly highlight what are the goal, the interests and the limits of our methodology compared to other methods. Thus, we add a paragraph at the end of the section 2.1:

The goal of this weather pattern classification methodology is to group days having similar atmospheric circulation pattern in a limited number of typical weather patterns. The weather pattern classification is thus defined at a regional scale and consists of the attribution of each observed day to one weather pattern. This regional weather pattern classification is then used at the local scale, for each daily rainfall series considered: the observed rainfall series is split into several rainfall sub-samples according to the weather pattern classification. This splitting is based on the hypothesis that rainfall events observed over a given area have different atmospheric geneses and thus that a rainfall series sampling based on days having similar atmospheric circulation patterns produces more homogeneous rainfall sub-samples than considering the observed rainfall series as a unique series (Garavaglia et al., 2010). Geopotential height fields are used for the definition of WP classification since they are interesting descriptors of regional rainfall patterns (e.g. Littmann (2000)).
The main advantage of this methodology is that it produces a rainfall-oriented WP classification, but days without any rainfall observations are also classified: the approach only needs a limited calibration period (typically 20-years) where both observed rainfall series and geopotential height fields are available over a given region in order to define several typical WP. The generated WP classification is finalized by using geopotential information. Then, it is possible to extend the classification beyond the calibration period by using only geopotential height fields. Since long geopotential height reanalyses exist, such as the National Oceanic and Atmospheric Administration

(NOAA) 20th Century Reanalysis - a global 6 hourly geopotential height fields from 1871 to 2011 (Compo et al., 2011) - or as the EMULATE reanalyses - a daily mean sea-level pressure reconstruction over Europe for the 1850–2003 period (Ansell et al., 2006) - the classification could be extended over significantly long periods. Boé and Terray (2008) applied a similar methodology combining both sea level pressure fields with daily precipitation fields for defining WPs over France and studying the link between WP frequency evolution and anthropogenic forcing for example. Applications of such approaches are particularly interesting for climate change impact studies, since only the geopotential height fields simulated by the General Circulation Models could be considered for predicting future WP frequencies for example.
The main limit of this methodology is that the WPs defined are only characterized by particular dynamical atmospheric situations (e.g. typical spatial distribution of low and high pressure systems over a given area) and not particular thermodynamic atmospheric situations (e.g. typical distribution of moisture amount over a given area). For example, considering dynamical and thermodynamical (such as moisture fluxes) description of atmospheric situations significantly improves the forecast performances (Obled et al., 2002), approach also included in statistico-dynamical downscaling methods (e.g. Beaulant et al. (2011)) or statistical downscaling methods (e.g. Mezghani and Hingray (2009)).
The weather pattern classification methodology is fully described and used in Garavaglia et al. (2010) for the definition of eight French WPs and in Brigode et al. (2012) for the definition of five Austrian WPs. It is summarised in the following four steps.

1.2.2 2/ Section 2

This section refers to previous published works. Nevertheless, as it is, it is difficult for the reader to fully understand the main stages of the methodology, the hypothesis and the uncertainty. As an example, the choice of the 2 geopotential (1000 hPa, 700 hPa) is motivated by results obtained for other climatic contexts and for different issues (forecast). How the authors can be certain that such results can be extrapolated to another region. Moreover, as far as the reviewer knows, the same authors (Obled, Bontron) also showed that the moisture flux is an important ingredient to improve the forecast. Why this latter variable is not taking into account in weather pattern classification in this present study?
Same as 2.2.1.

Moreover some choice needs to be better justified (e.g. definition of rainy days defined as the top 20% days? Why 20%? Can't we define a rainy day based on the spatial intermittency that has to be low? This section needs to be carefully reviewed in order i) to clarify the different steps of the clustering methods, ii) to add some information concerning its evaluation (intra class variability; inter class variability) and/or the associated uncertainty to the choice of the number of weather class, and iii) to justify the choice of some thresholds, variables.
We changed the description of the method in order to improve its clarity. We also added some information on the choice of final number of classes using intra-class inertia information (with a supplementary figure). Note also that considering a 10% threshold and considering a 25% threshold have been done but are not showed in the paper since it does not imply significant difference in the defined WP classification. Since none other classification were easily available over the considered domain, we did not compute classical scores in order to evaluate the performances of our classification in comparison with other ones. It could be an interesting perspective for further work.
Finally, we would like to once again highlight that the goal of the paper is not to present a new weather pattern classification method but is to apply an existing methodology which has been already applied in two different contexts (application to France in Garavaglia et al. 2010 and 2011, and application to Austria in Brigode et al. 2012), and to study the link between heavy rainfall events over Coastal BC and ENSO through a weather pattern classification.

1.2.3 3/ Section 3

For the reader who does not know in detail the geography of the studied region, it would be helpful to have an idea of the distribution of the raingauges as regard as the altitude.

We agree that this information is missing in the previous paper version. We thus modified the Figure 1 by adding a description of the elevation distribution over the studied area (Figure 1.a) and presenting the distribution of raingauges station elevations (Figure 1.b):

Location of the rainfall stations is reported in Figure 1a with blue and red dots, and elevation distribution of these stations is plotted in Figure 1.b.

Figure 1. (a) Location of the 177 rainfall series used for the Coastal BC WP definition (blue and red dots) and of the 45 rainfall series used for the quantification of the influence of ENSO on rainfall characteristics (red dots). Elevation data has been extracted from the SRTM 90m dataset (Jarvis et al. 2008). (b) Elevation distribution of the 177 Coastal BC rainfall series used for the Coastal BC WP definition. (c) Location of the 338 geopotential height grid points used for the Coastal BC WP definition.

Page 12, line 20 – 22: I do not understand why the SST is only average within the DJF period to characterize the winter period, previously defined as ONDJFM.

We agree that this difference of winter definition is a little bit confusing. The 3-months winter (December, January and February months) is used by Trenberth (1997) for the classical definition of El Niño / La Niña winters. Since this classification is widely used, we choose to not estimate SST index over a larger number of months. Moreover, considering 5-months winters (October, November, December, January, February and March months) rather than 3-months winters has no significant impact on the El Niño / La Niña winter classification.

1.2.4 4/ Section 4

The use of several acronyms, the non-consistency between the choice of color for Nino (red in Fig2 and then Blue in Fig6) and Nina (blue in Fig2 and red in Fig6), the poor quality of the figures, in particular Fig4 and Fig5, makes this section very difficult to understand.

We agree that legends of the different figures were particularly small and thus uneasy to read. We changed the legend sizes in the new paper version.

Page 13, Line 19: I do not understand the 8%. From Fig3, I am not able to extract this number. Please clarify.

We agree with the reviewer that this "8%" number is impossible to extract from the Fig.3. It corresponds to the average of *x values* of the Fig.3a, i.e. average reduction of mean rainfall amount observed during Nino winters compared to all winters, estimated over 45 stations in Coastal BC. We changed the text in order to clarify where this number is coming from (section 4.1):

For the majority of the 45 Coastal BC rainfall series considered, the average winter amount of rain is higher during Nina winter compared to all winters since numerous points are in the right part of the Fig3.a and average winter amount of rain is lower during Nino winter compared to all winters since numerous points are in the bottom part of the Fig3.a. Thus, significant differences are observed in terms of average winter amount of rain over Coastal BC, with about +8% rain during Nina winters compared to all winters on average over the 45 stations considered, and −8% rain during Nino winters compared to all winters on average over the 45 stations considered.

Figure 4 and the comments Page 4, lines 4 – 15: Figure 4 needs to be explicitly split in 3 different panels a), b) and c). Figure 4c needs to be enlarged. The legend needs to be enlarged. Mean precipitation should be explicitly given for each weather class.

We changed the Figure 4 (which is now counted as the Figure 5) by making the legend larger, plotting the monthly frequency with larger graphs, and adding a graph showing mean precipitation for each WP and each Coastal BC stations (section 4.2):

Figure 5 shows, for each of the five Coastal BC WPs, (a) the 1000 hPa geopotential height anomaly fields, (b) the station mean precipitation amount, (c) the station ratio between the mean precipitation amount and the general precipitation amount (considering all WPs) and (d) the monthly frequency estimated over the 1983-2003 period. WP1 groups rainy days throughout the Coastal BC region. WP2 is characterised by a North-Western–South-Eastern circulation which engendered particularly rainy events in the Washington State stations and Vancouver City area. WP3 groups days with South-West-East-North circulations, which bring a lot of rain in the central part of the Vancouver Island region. WP4 days are characterised by weaker South-West-North-East circulation which engendered rainy days in the Northern part of the Coastal BC region. Finally, the non-rainy pattern WP5 comprises typical anticyclonic situations, with essentially non-rainy days over Coastal BC region.

Figure 5. (a) 1000 hPa geopotential height anomaly fields, (b) station mean precipitation amount, (c) station ratio between the mean precipitation amount and the general precipitation amount (considering all WPs) and (d) monthly frequency for each of the five Coastal BC WPs, estimated over the 1983-2003 period. Black boxes indicate the spatial coverage of the geopotential space used.

I do not agree about the circulation direction of WP2. It is oriented North-Western – South-Eastern and not North-South. I do not agree with the sentence "WP4 … the same oriented circulations ..", the orientation is different and it should be mentioned that the circulation is also weaker that explain the weaker precipitation pattern. Please clarify these points.
We agree with the reviewer and we thus changed the description of the WP2 and WP4 (section 4.2):
… WP2 is characterised by a North-Western–South-Eastern circulation which engendered particularly rainy events in the Washington State stations and Vancouver City area. WP3 groups days with South-West-East-North circulations, which bring a lot of rain in the central part of the Vancouver Island region. WP4 days are characterised by weaker South-West-North-East circulation which engendered rainy days in the Northern part of the Coastal BC region. Finally, the non-rainy pattern WP5 comprises typical anticyclonic situations, with essentially non-rainy days over Coastal BC region.

Page 15, lines 10 – 13: I do not understand these 2 sentences as regard as Figure 6. Please clarify.
We agree with the reviewer, these two sentences describing the Figure 6 are not clear. We thus modified the text for improving the clarity (section 4.3):
The comparison of the relative scale parameter values plotted in Figure 6(a) reveals that several Coastal BC regions have WPs which are particularly intense in terms of heavy precipitation events related to the other WPs. Thus, WP2 scale parameter values are clearly the most important scale parameter values for the Washington State stations, coherently with the rainfall spatial distribution of the WP2 days (shown in Figure 5(c)), which are particularly rainy in this southern coastal area. Similarly, stations with particularly high WP3 and WP4 scale parameter values compared to the other scale parameter values are located in the Vancouver City area and on the Vancouver Island West Coast. Finally, scale parameter values of WP1 are close to the average value of the five scale parameter values for each station, highlighting a WP with the same relative importance over the whole domain and WP5 scale parameter values are regionally the lowest scale parameter values since these days are mainly days without any observed rain. It is thus interesting to note that Figure 6(a) is similar to Figure 5(c) in terms of spatial distribution of each WP relative importance: each WP is similarly important in terms of average amount of precipitation and in terms of scale parameter values compared to the other WPs.

Page 15, line 22: What do you mean by "more homogeneous sub-samples"
'More homogeneous sub-samples' means here 'sub-samples constituted by days having similar atmospheric circulation patterns', as now stated in the section 2.1. We added precisions on this expression (section 4.3):
This figure highlights that the Coastal BC WP classification is useful for splitting observed precipitation series into more homogeneous sub-samples (i.e. sub-samples constituted by days having similar

atmospheric circulation patterns) and thus identifying for each station the synoptic situations that generate the highest hazard in terms of heavy rainfall events

Figure 5 needs to be enlarged. Legends are too small as well as the table.
We changed the Figure 5 size.

Page 16, lines 22 - 23: the sentence needs to be reformulated.
We reformulated the sentence (section 4.4):
Significant but different changes are observed for WP2 and WP3: the WP2 is significantly more common during Nina winters and less common during Nino winters, while the WP3 is significantly more common during Nino winters and less common during Nina winters

Page 18, line 2: I read in Figure 7, -40% instead of -30%. Could you clarify?
We wrote in the paper the range of variability for each MEWP parameters, which is larger for scale parameter λ values (first line of the Figure 8), ranging from -40% to +40% than for u parameters (second line of the Figure 8), ranging from -30% to +30%.

Page 18, line 10: exprimed should be expressed
We changed this sentence (4.5):
The estimations of 1000-yr return period precipitation values (noted P1000 hereafter, expressed in mm) were then compared.

Figure 8: I do not understand the unit of the legend. Could you detail more.
There is no unit in this graph, the color is only showing where are the P_{1000} values estimated using Nino winters as inputs of the MEWP model (left graph) and the P_{1000} values estimated using Nina winters as inputs of the MEWP model (right graph) within the distribution of 1000 P_{1000} values estimated using 1000 random winter combinations, for each of the 45 rainfall stations. A station plotted with a green color means that the $P_{1000\ Nino}$ or the $P_{1000\ Nina}$ values are lower than the 0.05 quantile of the 1000 P_{1000} values. A station plotted with a purple color means that $P_{1000\ Nino}$ or $P_{1000\ Nina}$ values are greater than the 0.95 quantile of the 1000 P_{1000} values. We thus changed the explanation of this figure in the paper:
Differences between the different heavy rainfall estimations were then examined at the regional scale. The result of a significance test is plotted in Figure 10, which represents the degree of significance between P_{1000} values defined on Nino winters or on Nina winters for each of the 45 stations. The colour assigned to each rainfall station represents where are the P_{1000} values estimated using Nino winters as inputs of the MEWP model (Figure 10(a)) and the P_{1000} values estimated using Nina winters as inputs of the MEWP model (Figure 10(b)) within the distribution of 1000 P_{1000} values estimated using 1000 random winter combinations, for each of the 45 rainfall stations. A station plotted with a green color means that the $P_{1000\ Nino}$ or the $P_{1000\ Nina}$ values are lower than the 0.05 quantile of the 1000 P_{1000} values, while a station plotted with a purple color means that $P_{1000\ Nino}$ or $P_{1000\ Nina}$ values are greater than the 0.95 quantile of the 1000 P_{1000} values. Thus, green color and purple color highlight the stations where P_{1000} values estimated on particular winter set are significantly different from the total P_{1000} distribution.

In general in this section, few comments are given concerning the findings and the uncertainties associated to the methodology. How robust are the main findings?
The methodology used in our study for the quantification of ENSO influences on rainfall characteristics has been designed in order to evaluate the robustness of our findings: bootstrap simulations are performed in order to discuss the significance of difference between Nino and Nina heavy rainfall estimations.
For the definition of WP classification, we added some discussion and clarification on the methodological choices and limits of the WP classification method.

2 BIBLIOGRAPHY

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