Point-by-point response to the referees' reviews

The replies are written in bold type after the replies sent during the open discussion to each referee. The pages and lines numbers indicated in these replies are referred to the marked-up manuscript version.

Referee 1

Dear Referee,

Thank you very much for taking the time to read the manuscript and commenting on parts of it. We are pleased that you consider both the topic and findings interesting for HESS readers. As for the way it is written, we agree with you that the presentation of this research can be clarified. Below you will find the answers to the comments you made about the manuscript titled "Evaluation of drought representation and propagation in Regional Climate Model simulations over Spain" by A. Barella-Ortiz and P. Quintana-Seguí.

Once the other referee's comments are available, we will study them and see to complement the modifications proposed by this referee with yours.

General comments:

1. The title is misleading. This study is not only used RCMs but also LSMs and hydrological models (HMs).
   You are right in that the study uses LSMs and a hydrological model besides RCMs, but simulations from these are used as references to evaluate how RCMs represent droughts and the way precipitation anomalies propagate to soil moisture and streamflow anomalies. This is explained in the Introduction section (page 4, lines 1-5) and in Sect. 3 (page 7, lines 19 and 32 and page 8, line 11). Nevertheless, we will make it clearer in Sect. 3 (Datasets). In our opinion it is not necessary to modify the title as the evaluation of drought representation and propagation is performed for RCMs, but if the referees and the editor deem it necessary, we can think about an alternative.
   Modification:
   Following the advice of the Scientific Editing Service, the title has been changed to "Evaluation of drought representation and propagation in regional climate model simulations across Spain"

2. The abstract is not informative and poorly written. The objective of this study is not clear. For example authors stated that it is vital to study the evolution of drought in relation to climate change, and therefore better understanding processes involved in "it" is a key. This is not your objective to study the evolution of drought related to climate change.

Second, the methods and tools that authors used in the study are not well defined in the abstract. Last, the conclusion does not summarize the main findings.
We will rewrite the abstract indicating more clearly the main problematic and reason why we performed the study, the methodology employed, the RCMs analysed as well as the LSMs and hydrological model used as reference data, and the conclusions.
Modification:
The abstract has been rewritten.

3. The way the authors wrote their introduction can be concluded as follows: 1) many sentences in the introduction part are unclear and need to be re-written, 2) there is no clear story line, 3) the introduction is not well structured in reasoning, 4) missing many related references e.g., increase of drought in Mediterranean due to climate change, drought propagation, models uncertainty from WATCH.
We agree with you that the introduction should be clarified. We will restructure it in order to make clear the story line and reasoning. More references will be added too.
Modification:
Sec. 1 (Introduction) has been rewritten and clarified.

4. Section 2 and section 3 can be combined and need to be restructured. For example: 1) in section 2 the authors already discuss about the precipitation amount simulated by the models. 2) Section 3.2 discusses about the models, but LSM, RCM, and HM models are also models. So why authors separated them? 3) SURFEX and ORCHIDEE are LSM and why authors wrote them in different sub sections than LSM section (3.2.1). 4) I suggest the authors start with RCMs first and then followed by LSMs and HMs.
We wrote separately sections 2 and 3 because the first one describes the study area and the second one, explains i) the forcing and driving datasets and ii) the models (RCM, LSM, and HM) used in this study. We think that this separation is necessary and reasonable, but if the editor thinks that they must be fusioned, we can find a way to put them together.
    1. The reason why precipitation amount is discussed in Sect. 2 is to provide the reader with the general behaviour of the precipitation regime in Spain. This is key to analyse meteorological drought and its propagation. However, we agree with you that there might be redundant information regarding the precipitation regime in Sects. 2 and 5.1.1. We will rewrite them to avoid this issue.
    2. We agree with the author that Sects. 3.2 and 3.3 should be unified. There is a numbering error.
    3. This is similar to the previous point, there is a numbering error and Sects. 3.2.2 and 3.2.3 should be sub-sections of Sect. 3.2.1.
    4. We will follow your advice and restructure Sect. 3 as follows:

3 Datasets

3.1 Forcings and driving data

3.1.1 SAFRAN meteorological analysis

3.1.2 ERA-Interim

3.2 Models

3.2.1 Regional climate models

3.2.2 Land Surface Models

SURFEX

ORCHIDEE

3.2.3 Hydrological models

3.3 Observations

SURFEX and ORCHIDEE sub-sections will not be numbered, because only three levels of sectioning are allowed.

Modification

The structure of the manuscript has been modified. However, we did not follow the structure proposed previously in this comment. Section 3 (Datasets) (P5) has been modified in the following way:

3 Datasets

3.1 Regional climate models

3.2 Reference products

3.2.1 Meteorological drought reference

3.2.2 Soil moisture drought reference

3.2.3 Hydrological drought reference

We believe that this structure clarifies that RCMs have been analysed and SAFRAN, offline LSM simulations, SIMPA, and observed streamflow have been used as reference data. In addition, Tables 1 and 2 have been modified. Table 1 provides the RCMs analysed in the study and Table 2 lists the reference data used in the study.

5. Section 5 and 6 are well structured and also better in writing than other aforementioned sections. The conclusion is also expected. Of course the meteorological drought is better represented using climate model, and hydrological drought better represented using hydrological models. Moreover, authors also highlight the use of more models and indices, where in my opinion it is not necessary. This paper already used many models (RCMs and HMs). Different indices can be used but it depends on the goal of the study.
We are pleased that you find these sections better structured.

We think that your phrase "Of course the meteorological drought is better represented using climate model, and hydrological drought better represented using hydrological models" does not correctly describe the results of our study. Three types of drought (meteorological, soil moisture, and hydrological) are analysed, not two types. In addition, besides drought representation, we also analyse drought propagation: from a precipitation anomaly to soil moisture and streamflow anomalies. Finally, it is important to bear in mind that the study is focused on drought representation and propagation by RCMs and that the other types of models (LSMs and hydrological) are used as reference.

Regarding the perspectives, we believe that it is interesting to analyse more RCMs, because it helps to better understand uncertainties and improve modelling. As for the indices, we provide two examples that we believe are of interest to improve drought knowledge and modelling, one referred to a variable (temperature) and another one referred to a process (evapotranspiration). Both have an important impact on drought, but it is true that this also depends on the objectives. In our case, the objectives are to understand drought in a way as complete as possible.
Modification:
We hope that after the changes performed in the manuscript, the objectives, datasets, and methodology are clearer.

6. Some typos and grammar mistakes found in the texts.
   Line by line comment: L refers to Line and P refers to Page Note: Authors still need to pay attention for other sentences that are not mentioned here.
   We would like to thank you for pointing out the typos and grammar mistakes you found in the text. We will send the manuscript to a Scientific Editing Service to assure that the manuscript's English is correct.
   Modification:
   The manuscript has been sent to a Scientific Editing Service.

Below you will find the replies to the line by line comments.

1. L171: Already in line 1 I do not understand with your sentence. Here you stated: "Drought is an important climatic risk, of modeling.." what do you mean with that? Rephrase the sentence.
   The objective of the phrase is to inform that drought is an important climatic risk (which is expressed in a large number of scientific papers) and that drought is difficult to model because the interaction of several processes (atmospheric and continental), with different temporal scales, has to be taken into account. We will rephrase the sentence.
   Modification:
   The abstract's first paragraph has been rewritten as "Drought is an important climatic risk that is expected to increase in frequency, duration, and intensity as a result of a warmer climate. It is complex to model due to the interactions between atmospheric and continental processes. A better understanding of these processes and how the current modelling tools represent them and characterize drought is vital" (L1-3P1).

2. L4P1: You may remove "comma" from: "The study here presented, analyses.."
   The comma will be removed.
   Modification:
   The abstract has been rewritten and the beginning of the phrase has been modified to "The aim of this study is…" (L4P1)

3. L5P1: here you only mention RCM models. How about LSMs and HMs that you used?
   RCMs are mentioned because they are the models that we have evaluated in this work. However, as explained in the "General comments", number 2 reply, the abstract will be rewritten and the models whose simulations are used as references, will be mentioned.
   Modification:
   The datasets used as reference (SAFRAN, LSM offline simulations from ISBA-3L and ORCHIDEE, and a SIMPA hydrometeorological model simulation and observed streamflow) are included in the abstract (L10-12P1).

4. L6-7P1: You stated: ". . .these models improve meteorological drought representation, but. . ." It is unclear how you tested this? It was not stated in the previous sentences.
   This was tested by means of standardized indices computed using variables directly related to each type of drought:
   - SPI index computed using precipitation (meteorological drought).
   - SSMI index computed using soil moisture (soil moisture drought).
   - SRI and SSI index computed using runoff and streamflow, respectively (hydrological drought).

   The comparison between the indices provided by i) RCMs and ii) the reference data was performed by means of the RMSD and the Pearson correlation.
   As explained in the "General comments", number 2 reply, the abstract will be rewritten and the methodology will be informed.
   Modification:
   The text from the abstract informing about the methodology has been extended: "The analysis was carried out by means of standardized indices calculated using variables directly related to each type of drought: precipitation (SPI), soil moisture (SSMI), runoff (SRI), and streamflow (SSI)" (L5-7P1).

5. L8P1: You said: "These are mainly due to the relevance of model formulation" Is it model formulation or structure?
   We mean model structure. We would like to thank you for pointing this out.
   Modification:
   "Formulation" has been replaced by "Structure" (L15P1).

6. L13-14P1: You stated: ". . .impacts from recent climate related extremes show a significant vulnerability. . ." I do not understand this. Impacts from climate extremes show vulnerability?
   No, the ecosystems and human systems are vulnerable, as the phrase mentions. Maybe the phrase could be rewritten for better clarity. In fact, this is mentioned in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report.
   Modification:
   The phrase has been rewritten as "Impacts from recent climate-related extremes show that ecosystems and human systems are significantly vulnerable and exposed to current climate variability (IPCC, 2014)" (L20-21P1).

7. L15P1: Do you mean different development level such as less develop and well develop countries?
   Yes, we refer to well developed, developing, and underdeveloped countries. We will rephrase the sentence to make it clear.
   Modification:
   This text has been removed from the Introduction section to shorten and clarify it.

8. L18P1: Limited references. There are many.
   More references will be added.
   Modification:
   The reference Hoerling et al. (2012) has been included.

9. L22P1: There are more references for drought types, e.g., Van Loon (2015): hydrological drought explained, Mishra and Singh (2010): A review of drought concepts.
   We would like to thank you for suggesting these references. In fact they are already given in the text. Following your advice, we will also include them in this sentence.
   Modification:
   We have included Mishra and Singh (2010) and Van Loon (2015) in this sentence (L3P2).

10. L4P2: What do you mean with there are no thresholds for soil moisture drought?
    There are no standard determined values that once they are exceeded imply that there is a soil moisture drought. This is because this type of drought depends on other aspects, like the soil's type of vegetation or crop, its location, and season. But we agree that it is not clear now and we will remove this phrase from the text.
    Modification:
    The phrase has been removed from the text.

11. L6P2: Runoff is also one of hydrological drought where you also used in this study.
    We would like to thank you for pointing this out. Runoff will be included in the hydrological drought description.
    Modification:
    Runoff has been included in the hydrological drought description (L8P2).

12. L9P2: Here you introduce environmental drought. Can you give references about that? As far as I know, it is socio-economic drought.
    The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. WGII: Impacts, Adaptation, and Vulnerability lists the four types of drought given in the manuscript. Regarding environmental drought, it says that it is a combination of the other three types. We would like to thank you for pointing this out, since the reference provided is not the correct one. It should be IPCC (2007).
    Modification:

The reference IPCC (2014) has been corrected to IPCC (2007) (L3P2). The environmental drought has been removed from the text to make it more concise.

13. L10P2: You may add Van Loon et al. (2012): Evaluation of drought propagation in an ensemble mean of large-scale hydrological models.
    We would like to thank you for suggesting this references. In fact it is already given in the text. Following your advice, we will also include it in this sentence.
    Modification:
    The reference Van Loon et al. (2012) has been included (L11P2).

14. L12P2: I do believe it is not potential evapotranspiration but actual evapotranspiration.
    We will replace "potential" by "actual".
    Modification:
    Potential" has been replaced by "actual" (L13P2).

15. L12-13P2: This statement: ". . ..related to the availability of irrigation water in irrigated areas, thus depending on the hydrological drought" is unclear.
    Our purpose is to show that the different types of drought are related between them in different ways. A key factor defining the relation of soil moisture drought with the other types is irrigation.
    - Non irrigated areas: soil moisture drought appears slightly out of phase of the meteorological drought and depends on several factors (soil type, capacity to retain water, and evapotranspiration).
    - Irrigated areas: we can distinguish two cases:
        - In purely irrigated areas, soil moisture drought is directly related to the availability of irrigation water and, therefore, it depends on hydrological drought.
        - In regions where irrigation is carried out under unusual circumstances, to avoid crop loss, soil moisture drought is not due to a lack of irrigation water, but of the water content in the soil. In this case, soil moisture drought is related to meteorological drought.

    We will rewrite the text to make it more clear.
    Modification:
    The text has been extended: "This is also applicable to regions where irrigation is carried out under unusual circumstances, for example, to avoid crop loss. In irrigated areas, soil moisture drought is directly related to the availability of irrigation water and therefore depends on hydrological drought" (L13-15P2)

16. L15P2: You may write "some years"
    Following your advice, we will replace "year" by "years".
    Modification:
    The text has been removed from Sec. 1 to shorten and clarify the section.

17. L15-16P2: You wrote: “However, if there is no further delay in precipitation, it can occur that no hydrological drought is observed” What do you mean? Small precipitation amount may not alleviate hydrological drought.
    After re-reading the paragraph we think that it should be simplified, as it is not clear enough. What we mean is that soil moisture and hydrological drought are related to meteorological drought, but that meteorological drought alone does not explain the other kinds of drought.
    Modification:
    The text has been removed to avoid confusion.

18. L19-20P2: Repetition with first paragraph.
    The sentence will be removed from this paragraph.
    Modification:
    The paragraph has been removed for the sake of clarity.

19. L21-22P2: It is not necessary if you analyze drought without human influence where this may be the case in the models that you used.
    We agree with you that if the models used to analyse drought representation and propagation do not consider anthropization, human action does not have to be taken into account in the drought modelling process. However, we believe that it is important to include this information. The reason being that, at this stage of the Introduction section, we are talking about modelling drought from a general perspective, without being restricted to the RCMs’ characteristics. But this passage can be removed if necessary.
    Modification:
    Although the phrase has not been removed, it can be deleted if the Editor and referees deem it necessary.

20. L28P2: You may remove the word “used”
    The word “used” will be removed.
    Modification:
    The text has been rewritten.

21. L32-33P2: It is not clear sentence: “following this line”. Also you may replace “;” with “,”
    We will modify the sentence to “Other studies following this line of improvement are:...”. We will also replace the semicolon by a comma.
    Modification:
    - **The sentence has been modified: “Other studies analysing the effect of the accumulated period are Vicente-Serrano and López-Moreno (2005) and Edossa et al. (2009)” (L27-28P3).**
    - **We have used the Copernicus Publications LaTeX Package to prepare our manuscript. Semicolons are included when a list of references is provided.**

22. L4-5P3: I do not agree that RCM simulation is cheaper than GCM in terms of computing resources. First RCM needs GCM outputs for boundary model's inputs, second the computing resources depends on the resolutions of the model.
    We would like to thank you for pointing this out. We will remove this phrase from the text.
    Modification:
    The phrase has been removed from the text.

23. L13-14P3: Unclear sentence. What kind of tools and what will be improved?
    We will rephrase the sentence as "This will enable the development of drought prediction and management tools and the improvement of the existing ones".
    Modification:
    The text has been modified: "A better understanding of the different types of drought and their propagation processes is key to improving current and future drought representation and thus drought prediction and management tools" (L18-19P2).

24. L15P3: You may remove ","
    We will remove the comma from the first sentence.
    Modification:
    The phrase has been removed from the text.

25. L15P3: you may replace "capacity" with "capability"
    According to the Oxford dictionary, both capacity and capability can be defined as "the ability or power to do something."
    Modification:
    The text has been rewritten and neither "capacity" nor "capability" appear in it.

26. L17P3: Too many "it" can you define what are it?
    We are sorry that the sentence is not clear. If the "it" are removed, the sentence is as follows: "The comparison allows to analyse the RCM's contribution with respect to the global model that drives the RCM, and see whether if the RCM improves drought simulation". We will rephrase it to make it clearer.
    Modification:
    The text corresponding to the objectives of the study has been rewritten (L31P3-L3P4).

27. L19P3: Should be analyzed since they did the studies in the past.
    In comments 27 to 34, you suggest to write the text about the state-of-the-art using the past tense. We will follow your advice.
    Modification:
    The text has been written using the past tense.

28. L20P3: Replace "uses" with "used" and also define those three drought indices. What are they?
    Same reply as comment number 27.

29. L21P3: Replace use(s) with used. The word "too" is informal.
    Same reply as comment number 27.

30. L23P3: Replace analyse with analysed.
    Same reply as comment number 27.

31. L25P3: Replace use and study with their past tense form.
    Same reply as comment number 27.

32. L26P3: you may replace: "..studies are. . ." with ". . .those studies were. . ."
    Same reply as comment number 27.

33. L27P3: Replace analyse with analysed.
    Same reply as comment number 27.

34. L28P3: Replace are with were.
    Same reply as comment number 27.

35. L29-32P3: Why don't you combine these two sentences?
    In our opinion, the sentences should not be combined. The first sentence provides results about the study performed by García-Valdecasas Ojeda et al. (2017), while the second one informs about other studies that carry out similar analysis, but do not necessarily obtain the same results. However, since the expression "following this line" was not clear, we will rephrase the second sentence as: "Other studies analysing the effect of the time accumulated period are Vicente-Serrano and López-Moreno (2005), Vicente-Serrano (2006), and Edossa et al. (2009)".
    Modification:
    Section 1 (Introduction) has been rewritten and the information given in these sentences has been extended (L23-28P3).

36. L6P4: Missing "the". The standardized indices.
    In our opinion, there is no need to include "the" before "standardized indices".
    Modification:
    Once the text was rewritten, the Scientific Editing Service did not include "the" before "standardized indices".

37. L7P4: You may replace "with" with "using"
    We will replace "with" by "using".
    Modification:

The text has been rewritten (L2P4).

38. L8-10P4: Please write the full meaning of SSMI, SSI, and SRI first since this is the first time you introduce these acronyms.
    We will include the acronyms' description in the Introduction section.
    Modification:
    The meaning of SSMI, SSI, and SRI has been included in Sect. 4 (Methodology), since it is the first time that these acronyms are introduced (L11-13P9).

39. L11P4: Rewrite: ". . .we will detail the study are".
    The sentence will be rewritten as "The study area is detailed in the next section".
    Modification:
    This paragraph has been deleted.

40. L18-25P4: This paragraph should be in the result section.
    Same reply as the one from "General comments", number 2.
    Modification:
    The text about Fig. 2 has been moved to the Sect. 5 (Results) (L18-25P11).

41. L26-27P4: Can you elaborate more why soil moisture anomaly in spring may influence droughts and heatwaves? Also this statement is not belonging to study area.
    We agree with you that this sentence may not provide relevant information for the work presented in the manuscript. Therefore, we will rephrase it to explain that soil moisture deficits in Spring over Southern Europe favours drought propagation over Northern Europe. We believe that this information helps characterizing soil moisture drought over Spain and warns about its effect regarding drought propagation towards Northern Europe.
    Modification:
    This sentence has been rephrased and moved to the first paragraph of Sect. 2 (Area and study period) (L13-15P4).

42. L29P3: I suggest you to use different word for relief such as mountainous areas?
    We believe that this comment refers to page 4. In our opinion, "relief" is a valid word, as it refers to the difference in height from the surrounding terrain, but we can change it if necessary.
    Modification:
    The word "relief" has not been replaced by another one. However, it can be modified if the Editor and referees deem it necessary.

43. L31P4: What is "it" refers to?
    It refers to "a wide network of dams and river canals" that appears in the previous sentence. We will replace "It" by "This network".
    Modification:

This sentence has been removed from the text.

44. L32P4: Rewrite “to use” into “to be used”

    We will replace “to use” by “to be used”.

    Modification:

    This sentence has been removed from the text.

45. L2P5: You may write: “..a reduction of precipitation. . .”

    We will rephrase the sentence as: “However, a reduction of precipitation has been observed in Spring and Summer (de Luis et al., 2010), as well as an increase in the number of consecutive dry days (Turco and Llasat, 2011).”

    Modification:

    This sentence has been rephrased as “ Although precipitation does not show significant annual trends, observations show a reduction in spring and summer (de Luis et al., 2010) as well as an increase in the number of consecutive dry days (Turco and Llasat, 2011)” (L25-27P4).

46. L5P5: What is “it” refers to?

    It refers to “a rise in annual and seasonal temperatures” that appears in the previous sentence. We will replace “It” by “This rise”.

    Modifications

    “It” has been replaced by “This rise in temperature” (L28-29P4).

47. L8P5: You write: “. . .increase this type of drought”. In my opinion snow melt can increase or decrease the hydrological drought depend on early or late snow melt.

    In our opinion the text is correct, as we refer to the “advance of the thaw date” and, therefore, to early snow melt. However, we will include a sentence referring to the fact that streamflows may be affected by snow melt in different ways depending on the snow melt timing and resulting in an increase or decrease of hydrological drought. For this, we will cite Van Loon (2015).

    Modification:

    The phrase “ However, it should be noted that snow melt can affect streamflow and thus hydrological drought in different ways depending on its timing (Van Loon et al., 2010).” has been added (L32-33P4).

48. L17P5: Why don’t you combine paragraph 2 with 1?

    Paragraphs from lines 15 to 24 will be combined.

    Modification:

    The paragraphs describing SAFRAN have been combined (L5-15P6).

49. L23-24P5: This paragraph stands alone and can be combined with previous paragraph.

    Same reply as comment number 48.

50. L28P5: Rewrite: ". . .detailed in Quintana-Segui et al. (2016).

    We will rephrase the sentence as: "In Spain, SAFRAN was extended for a 35 year period (1979/1980 – 2013/2014) (Quintana-Seguí et al., 2016)."

    Modification:

    The sentence has been rephrased: " In Spain, SAFRAN was extended for a 35-year period (1979/1980 – 2013/2014) (Quintana-Segui et al., 2017) and was implemented and validated over the Ebro Basin (north-eastern Spain) (Quintana-Segui et al. 2016)" (L13-15P6).

51. L31P5: You may replace "in" with "for"

    We will replace "in" by "used for".

    Modification:

    The phrase has been removed the text.

52. L6P6: Again you may combine all paragraphs in this section (3.1.2) into 1. Paragraph 1 consists of two sentences, which are about ERA-interim and then paragraph two starts with the word "it". You should combine this paragraph since you still discuss about the same thing. Also you cannot start new paragraph with the word "it".

    Paragraphs from lines 4 to 9 will be combined. However, paragraphs from lines 10 to 14 will be left alone, since the first one does not describe ERA-Interim, as the previous ones do, and the last one informs about how ERA-interim will be referred to in the rest of the paper. In our opinion, this information should be given in separate paragraphs.

    Modification:

    The first two paragraphs describing ERA-Interim have been combined (L21-27P5).

53. L9P6: What is "it" refers to? Spatial resolution?

    It refers to "ERA-Interim". This phrase will be moved to line 4 (page6).

    Modification:

    This phrase has been moved (L23P5).

54. L11-12P6: please give reference.

    We will rewrite the text to better include the Ngo-Duc et al. (2005) and Weedon et al. (2011) references.

    Modification:

    The text has been rewritten as "However, biases in this type of forcing have a negative effect on LSM simulations, which can be corrected (Ngo-Duc et al., 2005; Weedon et al., 2011)" (L29-30P5).

55. L12-13P6: You write: ". . .they can be corrected". How?

    In our opinion that is out of the scope of this study. In addition, the Ngo-Duc et al. (2005) and Weedon et al. (2011) references, that deal with this issue, are provided.

This information is not included in the manuscript as it is out of the scope of the study. The references Ngo-Duc et al. (2005) and Weedon et al. (2011), which deal with this issue are given.

56. L1P7: Rewrite this sentence: “Since there is no observed truth for soil moisture available,. . .”
    The sentence will be rephrased as “Since there is no ground truth for soil moisture available, LSM offline simulations are used as reference in this study to analyse both soil moisture and hydrological droughts“.
    Modification:
    The phrase has been rewritten as “Offline LSM simulations are used in this study as a reference to analyse soil moisture drought because there is a lack of soil moisture data across mainland Spain that are suitable for studies that require a large spatial coverage” (L6-7P7). We have excluded “hydrological drought” because offline LSM simulations have been excluded from the hydrological drought analysis.

57. L8-9P7: You should write the full names first before the acronyms.
    The full names will be written before the acronyms.
    Modification:
    The full names have been written before the acronyms (L3-11P4).

58. L14P7: You may add “in” before 1 km resolution.
    We agree with you that a preposition should be added before “1 km resolution”. However, we think that “at” is better than “in”.
    Modification:
    The text has been rewritten as “...derived from the ECOCLIMAP land cover database at a 1 km resolution …” (L17P7).

59. L14P8: Rewrite the opening sentence.
    In our opinion the sentence is correct. However, we will move the reference of Ruti et al. (2015) to the end of the phrase. Regarding this paragraph, we propose to remove the last sentence. In our opinion, it is not necessary to provide further information about Med-CORDEX taking into account that references [Giorgi et al.(2009) and Ruti et al. (2015)] are provided.
    Modification:
    The opening sentence has been rewritten as “In this study, drought representation and propagation in three RCMs are analysed” (L4P5).

60. L18P8: Replace “is” with “are” since you mention about drought representation and propagation.
    We will replace “is” by “are”.
    Modification:

“Is” has been replaced by “are” (L4P5).

61. L20P8: You may reverse the words into “. . .represent physical processes in different ways. . .”

    The sentence will be rephrased as : “Each one of them uses a different surface scheme and, therefore, represent physical processes related to precipitation, soil moisture, and surface and sub-surface runoff in different ways”.

    Modification:

    The text has been rephrased as “...each one used a different surface scheme and therefore represented physical processes related to precipitation, soil moisture, and surface and sub-surface runoff in different ways” (L7-9P5).

62. L22P8: You used the name CNRM-RCSM4 but for previous sentence you use the name RCSM4 only. Please be consistent. Also for COSMO-CLM in L27.

    “CNRM-RCSM4” and “COSMO-CLM” will be introduced in Sec. 1, where we will explain that they are known as “RCSM4” and “CCLM4”.

    Modification:

    The models are introduced in Sect. 1 (L3-6P4).

63. L1P9: In the section 3.4, please mention the number stations that you used in your study.

    A total of 87 stations containing at least 95% of data in the study period were selected. This information will be included in the “Observations” section from Sec. 3.

    Modification:

    This information is included in Sect. 3.2.3 (L22-24P8).

64. L2-3P9: Missing verb in this sentence.

    The sentence contains the following verbs “belong” and “provide”.

    Modification:

    The text has been rewritten as: “Daily streamflow observations were also used as a reference in the hydrological drought analysis. These belong to the Spanish Ministry for the Ecological Transition, which provides data for basins comprising more than one region” (L3-4P9).

65. L3P9: You may write: “To obtain monthly time series. . .”

    We will write “time series”, instead of “series”.

    Modification:

    We have written “monthly series” instead of “series” (L11P8).

66. L4P9: Can you elaborate why south is not as represented as the north?

    We filtered the data in order to keep those stations with at least 95% of the data for the period studied and the stations kept are more abundant in the north. This could be due to i) southern basin authorities not submitting all data to the Ministry database, ii) that stations were installed later and thus the earlier part of the period is not covered, iii) problems of maintenance, iv) a combination of the three. We did not study the causes of this result.

Modification:

The text referring to the south of the peninsula not being as represented as the north has been removed.

67. L5P9: You may rewrite “to having” with “to have”

    If “to having” is replaced by “to have”, we will change the sentence’s meaning. What we intend to say is that we can either have i) more stations containing less data or ii) less stations containing more data. We decided to work with less stations with the certainty that these have at least 95% of data in the study period. In our opinion the sentence is correct. However, we can rephrase it to make it more clear.

    Modification:

    This phrase has been removed from the text.

68. L7-8P9: You wrote: “In this way, both studies complement each other. . ..” It is not clear sentence. What is in this way?

    It’s equivalent to saying “Like this”. The same methodology is used in the study performed by Quintana-Seguí et al. (2019) and the work presented in this paper. Therefore, both studies are complementary.

    Modification:

    “In this way” has been replaced by “Therefore” (L7P9).

69. L10-11P9: This sentence is not clear. You may write: “. . .we compute SPI and SSMI, which require precipitation and soil moisture data, respectively”.

    We propose to rephrase the sentence as: “For the meteorological and soil moisture drought analyses, we compute SPI and SSMI using precipitation and soil moisture data, respectively“.

    Modification:

    The text has been rewritten as “For the meteorological and soil moisture drought analyses, we computed the SPI and a Standardized Soil Moisture Index (SSMI) using precipitation and soil moisture data, respectively” (L10-12P9).

70. L14-16P9: Proper citations for all indices you mention here, except if you already did so before.

    In the text it is said that “We follow the spirit of the Standardized Precipitation Index (SPI)...” (L14P9). Therefore, apart from the SPI index computed using precipitation, other standardized indices are computed using other variables and following the same methodology as the one followed to compute the SPI (referenced in L6-7P3). The text provides these variables and their corresponding indices. We propose to increase the references to other studies that employ standardized indices computed using other variables besides precipitation.

Modification:
References about studies that employ standardized indices using precipitation, soil moisture, runoff, and streamflow are given in the Introduction section (L33P2-L6P3).

71. L1P10: You said the variable's time series is transformed from its original distribution to a normal one. What kind of distribution? Gamma, GEV, Pearson, etc?.
   There are several parametric distribution functions used to compute standardized indices. We propose to rephrase the sentence, since it may not clear if the text refers to standardized indices in general or to the indices computed for the study described in the manuscript.
   The reference to (Farahmand and AghaKouchak, 2015) is included in the text: " To solve this problem, we used the non-parametric methodology described by Farahmand and AghaKouchak (2015)" (L8-9P10).

72. L3P10: You may rewrite: ". . .in the meteorological case. . ." into "for meteorological case. . .."
   The text will be rewritten.
   Modification:
   The text has been rewritten as "The computation was carried out using monthly data for all indices. In the case of the SPI, a time series of the accumulated precipitation from the previous *n* months (with *n* being the index scale) was also calculated to perform the drought propagation analyses " (L4-6P10).

73. L4P10: You may change "for" with "from" and also missing verb.
   We will replace "for" by "from". The sentence contains the verb "to use" in its -ing form. However, we will rewrite the sentence as: "The computation is carried out using i) monthly data for all indices and ii) a time series of the accumulated precipitation from the previous n months (being n the index scale) for the SPI".
   Modification:
   We have replaced "for" by "from".The text has been rewritten (see previous comment).

74. L8P10: Why only for SPI-12?
   Considering 12 months results more robust due to seasonal reasons. We will mention this in the text.
   Modification:
   The following phrase has been included in Sec. 4.1: " Using results from an accumulation period of 12 months is particularly robust due to seasonal reasons" (L11P10).

75. L13-14P10: Please give reference.
   The reference McKee et al. (1993) will be given.

Modification:
The reference McKee et al. (1993) is given (L17P10).

76. L17P10: Please use better opening sentence.
    We will rephrase the sentence as "The methodology employed to analyse meteorological drought propagation is based on Barker et al. (2015)".
    Modification:
    The text has been rewritten as "The analysis of how meteorological drought propagates to soil moisture and hydrological drought is useful in hydrological resource management and allows the detection of similarities and differences in the way models address the physical processes that drive this propagation. The methodology employed to analyse meteorological drought propagation is based on Barker et al. (2016)" (L20-23P10).

77. L19P10: You may write actual evapotranspiration.
    We will remove "potential" from the text.
    Modification:
    The word "potential" has been replaced by "actual" (L25P10).

78. L15P11: You can combine second paragraph with the first.
    Paragraphs from lines 13 to 19 will be combined.
    Modification:
    Both paragraphs have been combined (L16-25P11).

79. L17-18P11: What do you mean with relief is a determining factor in distribution?
    The text aims to indicate that the way water from precipitation is distributed over a region is strongly influenced by the region's relief. We will modify the text to refer to water distribution from precipitation.
    Modification:
    The text has been rewritten as "The fact that precipitation is high over mountainous chains indicates the strong influence of relief, which is key in the way water from precipitation is distributed" (L22-23P11).

80. L21P11: Modeled precipitations usually have higher results than the observed and ERA-i. There are some papers show that.
    References will be included.
    Modification:
    The reference Sylla et al. (2010) has been included (L27-28P11).

81. L4P12: Drought in 2005-2006 does not coincide with those found "in" Belo-Pereira et al. (2011) but it occurred. So please rephrase.

The paper from Belo-Pereira et al. (2011) explains that “In 2005–2006, the available data sets (CRU, GPCC and ERA-I) agree on a generalized drought spell in all areas”. Therefore, drought in 2005-2006 is observed by the CRU, GPCC, and ERA-I data sets. In our work, the three RCMs analysed, as well as the ERA-I (RCMs’ driving data) and the SLR (reference data) data sets also show a drought in 2005-2006.
The text has not been modified because Belo-Pereira et al. (2011) showed that the datasets CRU, GPCC and ERA-I agree on a generalized drought spell in 2005–2006 and the RCMs analysed in the study we performed identify this spell too.

82. L6P12: It is hardly to see in the Figure. Can you write the number of months?
The number of months will be provided.
Modification:
The text has been extended and the drought spell’s number of months have been included (L4-7P13).

83. L2P13: typo for tan
We will correct the typographical error.
Modification:
The typographical error has been corrected.

84. L10P13: You may write: “The difference is the degree to which they deviate”
We will replace “The difference is the degree to which they do it” by “The difference is the degree to which they deviate”.
Modification:
The phrase has been rewritten as “The difference relates to the degree to which they deviate” (L31P13).

85. L11P13: What are “it” refer to?
The word “it” refers to the percentage of area affected by drought. The text will be rewritten as: “On the one hand, in 1995, RS4 overestimates the percentage of area affected by drought by 20 %, CL4 around 15 % and PMS does not reach 10 %. On the other hand, in 1996, PMS underestimates this percentage by more than 30 %, while RS4 and CL4 underestimate it by 10 %”.
Modification:
The phrase has been rewritten as “On the one hand, in 1995, RS4 overestimates the percentage of area affected by drought by 20%, CL4 by approximately 15%, and PMS by less than 10%. On the other hand, in 1996, PMS underestimates this percentage by more than 30%, while RS4 and CL4 underestimate it by 10%” (L31-34P13).

86. L12P13: What do you mean with “do it”
The words “do it” refer to the action of underestimating the percentage of area affected by drought. The text will be rewritten to make it clear (see the previous comment).

Modification:
See the modification from comment number 84.

87. L6P15: How about the white color in the table?
 Regions whose values are not within the colour scale are represented in white. We will inform this in the text.
 Modification:
 We have informed in the captions of Figs. 5 (P16) and 6 (P18) that regions whose values are not within the colour scale are represented in white.

88. L12P15: Please rewrite: ". . .RCMs compared between them. . ."
 We are not sure about the reason why it is proposed to rewrite this sentence. Our purpose is to show that if we compare drought representation by RCMs with other RCMs, we see changes in drought category representation. This is expected because, as explained in the text's previous phrase, changes in drought category representation are identified when RCMs are compared to LSMs (the reference data sets). But we can rephrase the text to make it more clear.
 Modification:
 The text has been rewritten as "In addition, the three RCMs compared among them also represent soil moisture droughts of different categories (second and third columns), as expected" (L8-9P16)

89. L14P16: Please elaborate more why SPI with higher accumulation period is slower.
 Fig. 5 shows the month scale at which the correlation between SSMI-1 (SSMI index computed for a time accumulation of 1 month) and SPI-n (SPI index computed for a time accumulation of 1 to 28 months) is maximum. Therefore, it can be interpreted as the temporal scale at which meteorological drought propagates to soil moisture drought. As the number of months increases, the models' dynamics decreases. Bearing this in mind, Fig. 5 does not show that the SPI is slower with higher accumulation periods, but that in the context of meteorological drought propagation to soil moisture drought, some models show slower dynamics (ORCHIDEE) than others (ISBA).
 We believe that the text from Sec. 5.2.2 (Propagation to soil moisture drought) together with Fig. 6 explain in a proper way the results obtained for the meteorological drought propagation to soil moisture drought. In addition, the methodology used is detailed in Sec. 4.2 (Meteorological drought propagation).

90. L3P17: you may rewrite: ". . .to the LSM with the surface scheme it is coupled to." Into ". . .LSM coupled with the surface scheme."
 We propose to rephrase the sentence as: "This becomes more evident, when an RCM is compared to the LSM that has the same surface scheme".
 Modification:
 The text has been rewritten as "This becomes more evident when a RCM is compared to the LSM that has the same surface scheme" (L7-8P17).

91. L7P18: Rewrite: “To single out stations”
    In our opinion, the text “To single out stations” is correct. According to the Oxford Dictionary, to single someone/something out is defined as “Choose someone or something from a group for special treatment”, which corresponds to the actions described in the text.
    Modification:
    This information has been moved to Sect. 3.2.3 (P8). The text has been rewritten, and the expression “To single out stations” has been removed.

92. L19-20P18: I thought LSMs should have better results for hydrological drought than GCMs.
    In the first place, it should be noted that hydrological drought is not discussed in this subsection. In our opinion, the ideal variable to analyse hydrological drought is streamflow. Since RCMs do not provide simulated streamflow, we propose to use aggregated runoff to compute a standardized index (SRI) to study hydrological drought. For this, we first compare streamflow and aggregated runoff between them to analyse their resemblance by means of the Kling-Gupta Efficiency (KGE). This subsection addresses the comparison between both variables (streamflow and runoff). In the second place, we would like to point out that there is no comparison between LSMs and GCMs, the comparison is between RCM simulations driven by ERA-Interim and offline LSM simulations forced by i) ERA-Interim and ii) SAFRAN. RCMs provide better KGE values than LSMs, which means that aggregated runoff simulated by RCMs performs better than aggregated runoff simulated by LSMs when compared to streamflow and when forced by the same forcing data (ERA-Interim).
    The aim of this subsection (Sec. 5.3.1 Streamflow and aggregated runoff comparison) should be clearer now.
    - **In Sec. 5.3 (Hydrological drought) it is said that in Sec. 5.3.1, streamflow and aggregated runoff will be compared.**
    - **The results showing the comparison between RCMs and offline LSM simulations (used as reference datasets) have been deleted to avoid misunderstandings. Therefore, the columns “ERA-ORC”, “ERA-ISB”, and SFR-ISB” have been removed from Table 4 together with the text referred to these columns.**
    - **Sec. 3 has been restructured to explain in a clearer way the datasets used as reference (for example, offline LSM simulations).**

93. L22P18: I saw 0.6 and not 0.7. Also you said that PMS behaves better over both basins. How do you define PMS is better? By average value or by color?
    The KGE value at station number 9002 for the comparison between RS4 and observations (lower table) is 0.7. The value 0.6 corresponds to the comparison between RS4 and the SIMPA model at the same station. We will modify the text to specify that 0.7 corresponds to the comparison between RS4 and observations.

We have identified PMS as the best performing according to the average value. We will include this in the text.

Modification:

The text has been rewritten as "Although RS4 is the RCM showing the highest KGE value (0.7 at station number 9002 for the comparison between RS4 and OBS), PMS performs better across both basins according to the average value" (L14P18-L2P19).

94. L4P19: Again what is white?

Regions whose values are not within the colour scale are represented in white. We will inform this in the text.

Modification:

The text has been rewritten as "Negative values, indicating poor performance, are marked in red. For the positive KGE values, a colour scale consisting of a blue (best performance between RCMs and i) SMP or ii) OBS) to red (worst performance between RCMs and i) SMP or ii) OBS) gradient via white has been included to facilitate reading" (L9-12P18).

95. L14P21: You may change from "the 9025 station" to "station number 9025"

We will replace "the 9025 station" by "station number 9025".

Modification:

The text has been rewritten as "... reference data in station number 9025 (which represents the Segre sub-basin)" (L6-7P19).

96. L10P22: What is extension?

Extension refers to the area affected by a drought event. We will replace "extension" by "area" to make the text more clear.

Modification:

The word "extension" has been replaced by "area" (L3P22).

97. L33P23: You may rewrite: "..that PMS' precipitation extremes are too strong" into ". . .that PMS simulates higher precipitation amount."

In our opinion, the phrase is valid. The paper provided as a reference (Dominguez et al., 2013) studies extreme precipitation indices. Therefore, the manuscript's text should refer to extreme precipitation.

The text has not been modified because the reference provided deals with extreme precipitation indices.

98. L9P24: I believe you cannot avoid the error but you can minimize the error.

We will replace "avoiding" by "minimizing".

Modification:

The word "avoiding" has been replaced by "minimizing" (L6P24).

99. L15P24: Replace use with used. Past tense passive sentence.
    We will replace “use” by “used”.
    Modification:
    The word “use” has been replaced by “used” (L12P24).

100. Figures: They are too small, cannot see them clearly.
    Figures will be enlarged.
    Modification:
    Figures and tables have been enlarged. However, there are axis and scale levels that might still be too small and might have to be enlarged more.

101. Table 6: I cannot find the number in bold. Can you also please write the correlation numbers for each color in the caption?
    We would like to thank you for pointing this out. Scales longer than 12 months will be marked in bold and the correlation ranges for each colour will be included in the caption.
    Modification:
    Scales longer than 12 months have been marked in bold and the correlation ranges have been included in the caption (P21).

We hope you will see a clear improvement in a revised version of the manuscript.

Yours sincerely,

Anaïs Barella-Ortiz

Referee 2

Dear Referee,

Thank you for taking the time to read the manuscript, as well as for commenting on parts of it. Below you will find the answers to the comments you made about the manuscript titled "Evaluation of drought representation and propagation in Regional Climate Model simulations over Spain" by A. Barella-Ortiz and P. Quintana-Seguí.

General comments

1. The language throughout makes it difficult to understand at times (for example, P23L18-19: It is not clear if this means that RCMs are not appropriate to calculate SPI at longer accumulation periods) and should be improved dramatically before publication.
   The manuscript will be sent to a Scientific Editing Service to assure that English is correct. Our purpose in P23L18-19, is to point out that the time accumulation period used to compute standardized indices influences the indices' added value. Therefore, we do not state that RCMs should not be used to compute SPI. However, the text will be rewritten to clarify this idea.
   Modification:
   - **The manuscript has been sent to a Scientific Editing Service.**
   - **The text mentioned in this comment has been simplified: "According to GarcÍa Valdecacas Ojeda et al. (2017) and Bowden et al. (2016), the added value of the SPI is influenced by the accumulation period employed. This is interesting to consider because soil moisture and hydrological droughts have different scales of propagation, and differences are also found in the propagation analysis in Sect. 5.2.2 and 5.3.3". (L11-14P23)**

2. The paper lacks clearly defined aims and applications, currently it reads as a modelling exercise rather than science to support real-world applications – this can be addressed by a better structured introduction as it currently jumps around without a coherent story (e.g. what is the problem, what have others done in the past, what is the research gap, what is the aim of this study and how this will address the research gap).The introduction and literature review also relies heavily on the IPCC reference, without reviewing peer reviewed publications (and where papers are introduced, they are often listed as 'other papers on the topic' such as P2 L32) and outlining the research gap this paper is aiming to fill. The lack of aims and disjointed nature of the paper make it difficult to reach the conclusions set out in the final section of the paper.
   Drought is a climatic risk, which will become more frequent, severe, and lasting due to a warmer climate. Therefore, it is important to know the evolution of drought. For this, the current modelling tools must be first evaluated. There are several studies about drought representation by models using different types of drought indexes. Our aim is to

contribute to these studies by analysing how regional climate models represent drought, as well as the propagation from a precipitation anomaly to a soil moisture and streamflow anomaly. In addition, our study complements a previous one by Quintana-Seguí et al. (2019) which analyses drought representation and propagation by land-surface models using the same methodology as we have employed. As a result, this study improves our current knowledge on the regional climate models' capability to reproduce both drought and its evolution.

The Introduction section will be rewritten and clarified. We will provide and explain more references to avoid lists. In addition, to increase the focus of the paper on the analysis of the RCMs, we propose to delete results from LSM simulations in the hydrological drought analysis (Tables 4 to 6: columns "ERA-ORC", "ERA-ISB", and "SFR-ISB"), together with the text referring to these.

Modification:

- **Section 1 (Introduction) has been rewritten.**
- **Section 3 (Datasets) has been restructured to clarify that RCMs are the models analysed and SAFRAN, offline LSM simulations, a SIMPA simulation, and observed streamflow are used as reference data.**
- **The results referred to LSMs shown in Section 5.3 (Hydrological drought) have been removed to avoid misunderstandings.**
- **The manuscript has been sent to a Scientific Editing Service.**

3. It has not been made clear why this modelling approach was used. The assertion on P6L20 that the atmospheric feedback not being accounted for makes LSMs a good tool to study drought because they can be treated like physically distributed hydrological models, does not provide explanation – why do you want them to behave like a physically distributed model?

The reasons for using LSM offline simulations as reference in the soil moisture drought analysis, are the following:

1. Using offline simulations avoids biases due to the atmospheric model and the coupling between LSM and atmospheric model.
2. There is no observed truth available for soil moisture (P7,L1-2) that covers mainland Spain, thus we use offline simulations as a reference.

We will rewrite the text in P6L20 to explain clearer that atmospheric model biases are excluded in LSM offline simulations.

Modification:

The text has been rewritten as "Offline LSM simulations are used in this study as a reference to analyse soil moisture drought because there is a lack of soil moisture data across mainland Spain that are suitable for studies that require a large spatial coverage. Internally, in RCMs, LSMs are bidirectionally coupled to the atmospheric model to simulate surface processes. However, when LSMs are run offline (forced by gridded databases), biases due to the atmospheric model and the coupling between the atmospheric model and the LSM are avoided. This

makes offline LSM simulations good reference datasets to study drought" (L6-10P7).

4. You don't mention or address the issue of uncertainty – what about the uncertainties of the modelling approach? Could you explore this using a multi-model ensemble?
   Yes, uncertainty is a very important topic and, in fact, we are already dealing with it. The main objective of this article is to evaluate drought properties in RCM simulations. We are performing the analysis on three different models and these provide different results in terms of drought indices and, specially, drought propagation. With only three models we already show that the values of n_x (time scale of propagation of drought) are very different for both soil moisture and runoff. Adding more models would show the spread with more detail, but we believe that the differences with three models are large enough to show that RCM developers should look at these issues and RCM users should take them into account.
   Modification:
   The issue of uncertainty has been included in Section 6 (Discussion) (L18-22P23).

5. In many places, there is text seemingly in the wrong section of the paper, for example P3L33-P4L4 should more likely sit in the data/methods section as this is detailed for the introduction. P5L1-8 would be better placed in the introduction. P11L24-27 would be better placed in the discussion describing why there were discrepancies between the modelled outputs. The authors should review the text to ensure that descriptions of data and methods and discussion text are in the appropriate sections.
   - P3L33-P4L4 should more likely sit in the data/methods section as this is detailed for the introduction. In our opinion it is not too detailed for the introduction as we list the RCMs analyzed and the references used. These are further explained in Section 3. However, if the referees and editor deem it necessary, this part of the text from the Introduction section can be shortened.
     - **The RCMs and the reference data used are listed in Sect. 1 (Introduction). All of them are explained in Sect. 3 (Methodology), the RCMs are detailed in Sec. 3.1 (Regional Climate Models) and the reference data in Sec. 3.2 (Reference products).**
   - P5L1-8 would be better placed in the introduction. The text describes drought in mainland Spain, which is the area of study. That is the reason why it is located in Section 2 (Area and study period). However, it can be moved to the Introduction Section if the referees and Editor deem it necessary.
     Sect. 2 has been kept. However, some of the text has been moved to Sect. 5.1.1 (Mean annual precipitation comparison).
   - P11L24-27 would be better placed in the discussion describing why there were discrepancies between the modelled outputs.
     We propose to move the phrases " There are few pluviometers in mountainous areas, probably causing an underestimation of precipitation over these regions. However, this effect is limited to mountainous areas" to the Discussion Section.

However, we believe that lines 26 and 27 should remain in Section 5.1.1, because they describe CCLM4 mean precipitation over mainland Spain.
Modification:
The phrases "There are few pluviometers in mountainous areas, probably causing an underestimation of precipitation over these regions. However, this effect is limited to mountainous areas." have been removed from the text.

6. Section 3.1: this should have more introductory information before diving into the detailed descriptions of SAFRAN and ERA, in 3.1 please outline what variables you use and what they are needed for before describing them in turn.
More introductory information will be provided before the subsections describing SAFRAN and ERA-Interim. Besides referring to Table 1, we will explain why these were chosen as driving data and reference dataset.
The variables used in our study to compute standardized indices (precipitation, soil moisture, streamflow, and total runoff), are detailed in Section 4.1 (Drought indices calculation) (P9L14-16), not in Section 3.1. However, we do provide a description of SAFRAN's precipitation in Section 3.1.1 because it is considered our reference dataset for the meteorological drought analysis.
Modification:
The variables used to compute the standardized indices are provided in the Sect. 1(Introduction) as well as for which drought analysis they are used.
Sect. 3.1 has been modified to make the manuscript clearer:
    - **Since ERA-Interim is the driving data of the three RCMs analysed in this study, it is described in Sect. 3.1 (Regional Climate Models) (L21-32P5).**
    - **SAFRAN is described in Sect. 3.2.1 (Meteorological drought reference) (P6). In the description we explain why it is chosen as the reference dataset for the meteorological drought analysis. Although, all the variables estimated by SAFRAN are provided, focus is made on precipitation, since it is the variable used to compute the SPI.**

7. In Section 3 the RCMs are introduced third but surely start the modelling chain, I suggest you introduce these first, then the LSMs then Hydrological Models. Was it necessary to calibrate and validate your models – how did you do this?
Yes, we can clarify this point. You mention "modelling chain" as if the RCMs were driving the LSMs (one way forcing). We fear there is a confusion here. The RCMs contain themselves a LSM, which is coupled with the atmospheric model of the RCM. We are taking the outputs of the RCM's LSM variables directly from the MedCordex database. Thus, there is no "modeling chain" in this regard. This is, we are not forcing standalone LSMs with the outputs of the atmospheric variables of an RCM simulation. We also use standalone offline LSM simulations, forced by ERA-Interim and SAFRAN, in order to have comparison points.

That being said, we propose to restructure Sect. 3 as follows, in order to provide more clarity:

- 3 Datasets
  - 3.1 Forcings and driving data
    - 3.1.1 SAFRAN meteorological analysis
    - 3.1.2 ERA-Interim
  - 3.2 Models
    - 3.2.1 Regional climate models
    - 3.2.2 Land Surface Models
      - SURFEX
      - ORCHIDEE
    - 3.2.3 Hydrological models
  - 3.3 Observations

SURFEX and ORCHIDEE sub-sections will not be numbered, because only three levels of sectioning are allowed.

Concerning model calibration, the situation is as follows:

1. We took RCM data from the MedCordex database. RCM modelers do tune their models, but this information is not available to us. In this regard, we simply are users of the RCM outputs.
2. We used an ERA-ORCHIDEE simulation, which was provided to use by Jan Polcher (IPSL). We do not know how IPSL calibrates its LSM.
3. We performed ERA-SURFEX and SAFRAN-SURFEX simulations. We did not calibrate SURFEX. We used default values for all non physical variables (i.e. subgrid runoff). The corresponding flows were calculated using the RAPID river routing scheme. The Muskingum parameters were not tuned, we used default values too. Concerning SURFEX modelled flows, we have proposed in comment number 2 to delete results from LSM simulations in the hydrological drought analysis.
4. We also used the outputs of the SIMPA model, as a reference. This model is heavily calibrated. The model calibration and run were performed by CEDEX, the Spanish institute that provides the reference natural streamflow simulations to the Ministry for the Ecological Transition and the basin authorities. We are users of these simulations and do not have access to information on the calibration.

   This information can be included in the manuscript if the referees and editor deem it necessary.

   Modification:
   The structure of the manuscript has been modified. However, we did not follow the structure proposed previously in this comment. Section 3 (Datasets) has been modified in the following way:
   3 Datasets
   - **3.1 Regional climate models**

3.2 Reference products

3.2.1 Meteorological drought reference

3.2.2 Soil moisture drought reference

3.2.3 Hydrological drought reference

We believe that this structure clarifies that RCMs have been analysed and SAFRAN, offline LSM simulations, SIMPA, and observed streamflow have been used as reference data. In addition, Tables 1 and 2 have been modified. Table 1 provides the RCMs analysed in the study and Table 2 lists the reference data used in the study.

8. A lot of detail is provided about the LSMs which is published elsewhere and appears to pad the paper, much of the model background can be removed – the focus should be on why the models were chosen and what they will be used for.

   LSMs' descriptions will be shortened and the reason why they were chosen and the use they were given in the study will be explained.

   Modification:

   The LSMs' description has been shortened. Apart from a brief description, the text explains the following:

   - **Offline LSM simulations are used as reference datasets in the soil moisture drought analysis (L6P7).**
   - **The offline LSM simulations selected are used as surface schemes by two of the RCMs analysed in this study (L10-11P7).**

9. Section 3.4: It would be useful to include a map of the observation stations used- how many stations were used? Only 8 across the whole of Spain? Why not more – there must be more than 8 stations that have 95% data completeness?

   You are right, there are more than 8 stations with 95% data completeness. However, our criteria to select them was more demanding:

   - 95% data completeness: This assures that the observation monthly series have few gaps.
   - Area greater than 10^3 km^2: Since streamflow is approximated by runoff, it is likely to perform poorly in small basins considering the coarse resolution of the RCM simulations. Therefore, the analysis was limited to large areas.
   - KGE between SIMPA and the observations greater than 0.5: To consider a near-natural regime.

     These criteria are explained in Section 5.3 (P18L1-11). The second one was the most restrictive, since only 13 stations out of the 87 with 95% data completeness have an area greater than 10^3 km^2.

     Modification:

     This information has been moved to Sect. 3.2.3 (L11-21P8), where the reference datasets for the hydrological drought analysis are explained.

10. P18L8: What evidence or scientific literature did you use to select the ‘arbitrary’ KGE of 0.5? Later in Section 5.3.1 you say performance of CL4 is poor because KGE is generally below 0.5, but the best performance is for RS4 with KGE of 0.7 – is this enough of a difference between poor and best (reading ‘good’) performance?
    - P18L8: What evidence or scientific literature did you use to select the ‘arbitrary’ KGE of 0.5?
      In order to validate the aggregated runoff of the RCM simulations, we needed gauging stations that were as natural as possible and whose corresponding basins were large enough to be compared to a low resolution RCM. This is difficult in Spain, due to the high degree of human influence. Thus, we needed to have enough large basins that were as natural possible. We thought that a high value of KGE between SIMPA (naturalized flow) and the observations was an indicator of natural regime. Then, we had to set a threshold of the KGE. We tested different values and 0.5, was a reasonable compromise between “near natural regime” and “enough number of stations”. It is true that 0.5 is not very high, and thus some human influence can be present, but we had to draw the line somewhere and we did a sensitivity analysis based on our own judgement. Thus, the value is not as “arbitrary” as the text implies. We propose to remove the word “arbitrary” from the text, as it is misleading, and clarify the procedure we followed to select this value.
      Modification:
      The text has been rewritten (L15-21P8).

    - Later in Section 5.3.1 you say performance of CL4 is poor because KGE is generally below 0.5, but the best performance is for RS4 with KGE of 0.7 – is this enough of a difference between poor and best (reading ‘good’) performance?
      Regarding the difference between poor and best, the text in Section 5.3.1 does not refer to a “best performance”:
        - It compares RCMs with LSMs and states that two RCMs provide better KGE than the LSMs with the same surface scheme (P18L19-20).
        - We say that CCLM4 behaves poorly because we have set a minimum threshold of 0.5 and all KGE values provided by the comparison of CCLM4 and SIMPA are lower.
        - When RCSM4 and PROMES are compared between them, it is said that RCSM4 shows the best KGE value for one station, but that PROMES behaves better over both basins (P18L22).

      We propose to modify the text so that it is clearer that CCLM4 provides the worst performance of the three RCMs analyzed and to replace “ PMS behaves better” by “PMS performs better”. In addition, we will explain that PMS is identified as the best performing RCM out of the three RCMs analysed according to the KGE average value. In this section, We will also avoid using adjectives such as “poor” to qualify the KGE values, sticking more to the numerical values, in order to avoid misleading the reader with our own subjective views.

Modification:

The text has been rewritten as " Focusing on the positive KGE values, CL4 has the worst performance, since the values are below 0.5. Although RS4 is the RCM showing the highest KGE value (0.7 at station number 9002 for the comparison between RS4 and OBS), PMS performs better across both basins according to the average value" (L12P18-L2P19).

11. Section 5.3.1 – why were the temporal analysis not shown? If you only have 8 gauging stations, it would be simple to include time series plots showing the modelled ensemble data against the observations.
Temporal analysis are not shown in order to reduce the number of figures. The main result of this section is Table 4, which compares streamflow and aggregated runoff to analyse the performance of RCMs by means of the KGE. The temporal series provides additional information, which in our opinion is not necessary to include. However, if the referees and the editor deem it necessary, we can include them.
A figure showing the temporal analysis has not been included. As explained in the previous reply, the main result of this section is Table 4.

12. Table 6: This might be better as a figure with the catchment areas coloured by SPI-nx – as readers we don't know where your catchments are, how do the results vary spatially? What might the effect of catchment properties be on the propagation process? How well do the different models represent these catchment properties?
We thought about making a similar figure, but we discarded it. The figure we planned to make was to plot the points of the stations, graduating their color in function of the value of n_x. However, as we are using only 8 stations (because we want to compare the simulations to observations from near natural flow gauging stations), the maps were not really necessary (a lot of empty space, with just a few colored points). You propose to color the areas of the basins. This can be done, but, again, with only 8 stations, the resulting colour areas would not be meaningful enough. However, we propose to include a figure showing the relief, river network, and the ubication of the gauging stations. We will include, if possible, the catchment areas defined by each station.
Modification:
A figure showing the relief, river network, and the location of the gauging stations has been included (Fig. 1, P9).

13. Table 6: What r values are associated with the Evans classification? How significant are these correlations? The bold type face mentioned in the caption is not obvious in the table.
    - The correlation ranges from the Evans (1996) classification will be included in the caption.
      Modification:
      The correlation ranges have been included in the caption of Table 6 (P21).

- Correlations are 95% significant. This information will be included in the manuscript.
  Modification:
  The phrase "... and the Pearson correlation coefficient (r) at a 95% significance level." has been included in Sect. 4.1 (L15P10)
- Scales longer than 12 months will be marked in bold.
  Modification:
  Scales longer than 12 months have been marked in bold in Table 6 (P21).

14. P22L4: why do you believe standardised indicators are appropriate for this study? This should have been outlined previously.
    Standardized indices define drought according to the variability of a given variable (P4L6 and P9L9-10). They allow to study different types of drought depending on the variable selected. In addition, variability is very important regarding drought analysis and it is the basis of these indices. We propose to extend the text to make clearer why we used standardized indices.
    Modification:
    The text from Sect. 4 has been extended to mention the importance of variability, which is key in standardized indices, in drought analysis (L10P9).

15. P22L10: what is meant by event extension? The duration and intensity (and extension) of events is not described elsewhere nor shown in any figures – what do you refer to here?
    By "event extension" we refer to the area affected by a drought event. We will rewrite the text to make it clearer.
    The duration and intensity of events is shown in Fig. 2, while the extension (area) is treated in Fig. 3.
    Modification:
    The word "extension" has been replaced by "area" (L3P22). More information about drought duration and intensity has been included in Sect. 5.1.2 (L4-13P13).

16. In general the figures were too small and labels too small to read. You should avoid the red-blue colour schemes of Tables 3-6, they are not appropriate for those who are colour blind. You can check whether your figures are colourblind friendly here: http://www.color-blindness.com/coblis-colorblindness-simulator/ or by using the CVSimulator app
    We will increase the figures' size. We will also check the tables in the Color BLIndness Simulator and change the colour schemes to make them more appropriate to colour blind people. Thank you for pointing this out.
    Modification:
    - **The figures have been enlarged. However, there are axis and scale levels that might still be too small and might have to be enlarged more.**

- **The colour schemes from Tables 3 to 6 has been changed from green-red to blue-red and from green-blue-red-white to blue-yellow-red-white. We hope that these colour schemes are more colourblind friendly.**

17. In regards to the Barker et al. (2015), you have cited the Discussions paper, please cite the final 2016 paper (https://www.hydrol-earth-syst-sci.net/20/2483/2016/hess-20-2483-2016.html).
    Thank you for pointing this out. We will cite Barker et al. (2016).
    Modification:
    Barker et al. (2016) has been cited (L23-24P10).

18. On P3L31 Lopez-Morreno's name has been misspelled.
    Thank you for pointing this out. We will correct the reference.
    Modification:
    The reference has been corrected (L27P3).

19. The tense throughout is the present tense, however, research is conventionally written up in the past tense (as it is work that has been completed), please correct this in the next version of the paper.
    We propose to write the state-of-the-art from the Introduction section, as well as the Methodology section in the past tense and leave the results description in the present tense.
    Modification:
    The state-of-the-art from the Introduction section, as well as the Methodology section have been written in the past tense.

We hope you will see a clear improvement in a revised version of the manuscript.

Yours sincerely,

Anaïs Barella-Ortiz

Relevant changes made in the manuscript

- Sect. 1(Introduction) has been rewritten.
- Sect. 3 (Datasets) has been restructured to distinguish the RCMs analysed in the paper from the reference datasets used (SAFRAN, offline LSM simulations, SIMPA simulation, and observed streamflow). The section is divided into two subsections: i) Regional climate models and ii) Reference products. Tables 1 and 2 have also been modified to differentiate RCMs from the reference datasets.
- A figure including the river network, relief and the location of the gauging stations selected in the hydrological drought analysis has been included (Fig. 1).
- The results referred to offline LSM simulations showed in Sect. 5.3 (Hydrological drought) have been removed to avoid possible misunderstandings with the aim of the study.
- The manuscript has been sent to a Scientific Editing Service.

Marked-up manuscript version

A manuscript marked-up version is included below. Changes are highlighted in red. A section title that is highlighted in red corresponds to a new section or to a section that has been largely modified.

Evaluation of drought representation and propagation in Regional Climate Model simulations across Spain

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Abstract. Drought is an important climatic risk that is expected to increase in frequency, duration, and intensity as a result of a warmer climate. It is complex to model due to the interactions between atmospheric and continental processes. A better understanding of these processes and how the current modelling tools represent them and characterize drought is vital.

The aim of this study is to analyse how Regional Climate Models (RCMs) represent meteorological, soil moisture, and hydrological drought as well as propagation from precipitation anomalies to soil moisture and streamflow anomalies. The analysis was carried out by means of standardized indices calculated using variables directly related to each type of drought: precipitation (SPI), soil moisture (SSMI), runoff (SRI), and streamflow (SSI). The objective is to evaluate how these models modify drought and whether they improve its representation compared to their driving and reference datasets.

The RCMs evaluated are the CNRM-RCSM4, COSMO-CLM, and PROMES. All of the simulations were obtained from the Med-CORDEX database and were forced with ERA-Interim. The following datasets were used as references: SAFRAN (meteorological drought), offline land surface model simulations from the ISBA-3L and ORCHIDEE (soil moisture), a SIMPA hydrological model simulation and observed streamflow (hydrological drought).

The results show that RCMs improve meteorological drought representation. However, uncertainties are identified in their characterization of soil moisture and hydrological drought, as well as in drought propagation. These are mainly explained by the model structure. For instance, model structure affects the temporal scale at which precipitation variability propagates to soil moisture and streamflow.

1 Introduction

Impacts from recent climate-related extremes show that ecosystems and human systems are significantly vulnerable and exposed to current climate variability (IPCC, 2014). In addition, most of these impacts have been observed to increase in climate change scenarios. For instance, drought frequency has increased in Mediterranean regions during recent decades (Mariotti, 2010; Sousa et al., 2011; Hoerling et al., 2012).

Drought is a complex phenomenon with important impacts on the environment (Reichstein et al., 2013; Vicente-Serrano et al., 2013) as well as on society and the economy (FAO, 2009; Owens et al., 2003). There are several types of drought (IPCC, 2007; Mishra and Singh, 2010; Van Loon , 2015) depending on which part of the system suffers from water deficit:

- Meteorological drought: corresponds to a period during which precipitation has been considerably lower than its average level.
- Soil moisture drought (also known as agricultural drought): is due to a deficit of water in the soil's unsaturated zone, making it impossible to cover the crop's needs.
- Hydrological drought: occurs when runoff, streamflow and water levels in rivers, lakes, and groundwater are low. A more precise definition refers to superficial and groundwater water availability decreases in managed systems, affecting water demand.

Since precipitation deficits propagate through the hydrological system (Wilhite, 2000; Van Loon et al., 2012b), drought types are interrelated. Soil moisture drought is slightly out of phase with meteorological drought in non-irrigated areas and depends on several factors, such as the soil type and capacity to retain water as well as actual evapotranspiration. This is also applicable to regions where irrigation is carried out under unusual circumstances, for example, to avoid crop loss. In irrigated areas, soil moisture drought is directly related to the availability of irrigation water and therefore depends on hydrological drought. Hydrological drought is also affected by meteorological drought but generally at a larger temporal scale than soil moisture drought. Therefore, each system component is characterized by its own propagation dynamics and memory.

A better understanding of the different types of drought and their propagation processes is key to improving current and future drought representation and thus drought prediction and management tools. Regional Climate Models (RCMs) can help in this task. One of their greatest advantages is their adaptation to the regional scale (Feser et al., 2011).This allows us to use regional observations and to increase the model's physical parametrization complexity. Such models are suitable for drought analyses because they are frequently performed at the catchment scale. Another important aspect of RCMs is that these models are used to develop regional climate change scenarios through donwscaling processes (Jiménez et al., 2013). In addition, using high resolution permits RCMs to be used to perform studies of atmospheric phenomena at a small scale. However, drought is difficult to model, since complex interactions between atmospheric and continental surface processes must be combined together with human action (Van Loon et al., 2012a). Furthermore, the relationships among drought types add complexity to such modelling.

Drought studies have gained interest in recent years due to increasing concern regarding i) complexity in hydrological resource management, ii) the escalation of the frequency, severity, and duration of extreme events, iii) the increase in both the vulnerability to such events and the probability of being affected by them, and iv) climate change (Andreadis and Lettenmaier , 2006; Mishra and Singh, 2010, 2011; López-Bustins et al., 2013; Jenkins and Warren, 2014). Drought studies are normally performed using drought indices, among which the Palmer Drought Severity Index (PDSI) (Palmer, 1965) and the Standardized Precipitation Index (SPI) (McKee et al., 1993) are two of the most widely used. According to Farahmand and AghaKouchak (2015), standardized indices can be computed using other variables besides precipitation. For instance, Xu et al. (2018) used data from the Soil Moisture Active Passive (SMAP) satellite and the North American Land Data Assimilation System (NLDAS) to compute a standardized soil moisture index for drought warning. Shukla and Wood et al. (2008) calculated a standardized runoff index using a simulation from the Variable Infiltration Capacity (VIC) model. They compared its behaviour to that of the SPI and concluded that a runoff-based index has the potential to complement other climate indices. Vicente-Serrano et al. (2012) analysed a method to compute a standardized streamflow index to compare streamflow hydrological conditions both spatially and temporally in a precise way.

Several studies analyse meteorological drought by means of RCMs. For instance, Maule et al. (2013) used the SPI and a version of the PDSI to analyse drought representation by 14 RCMs from the ENSEMBLES project (van der Linden and Mitchell, 2009) at a European scale. Blenkinshop and Fowler (2007a, b) analysed drought characteristics (such as duration and severity) using RCMs from the PRUDENCE project (Christensen et al., 2007) across Britain and at a European scale by means of the Drought Severity Index (DSI). PaiMazumder et al. (2013) and Masud et al. (2017) analysed projected changes to drought aspects in Canadian prairies by means of RCMs. Both studies used an ensemble, but the first one used three severity drought indices computed following Bryant et al. (1992)'s concept of accumulated monthly precipitation deficit, while the second one used the SPI and PDSI. Other studies employed RCMs to analyse drought trends (Wu et al., 2016) or to study the capacity of downscaled data to represent drought spells (Anagnostopoulou, 2017). RCMs are also used in soil moisture and hydrological drought analyses. However, there have been fewer studies about these types. Vu et al. (2015) and Meresa et al. (2016) studied hydro-meteorological drought by computing precipitation and runoff standardized indices using simulations of the Weather Research and Forecasting (WRF) RCM driven by General Climate Models (GCMs). Wang et al. (2011) studied the impact of climate change on drought. They analysed drought characteristics and the propagation impacts on meteorological, soil moisture, and hydrological droughts in Illinois using GCM-RCM nested simulations. The RCM used was the fifth-generation Pennsylvania State University-National Center for Atmospheric Prediction (PSU-NCAR) Mesoscale Model (CMM55) (Dudhia et al., 2000). Soil moisture and hydrological drought are also analysed by setting a given accumulated period to compute the drought index. García-Valdecasas Ojeda et al. (2017) studied how the WRF model improved dry and wet period detection using the SPI and SPEI computed at 3 and 12 month time scales to study episodes related to soil moisture and hydrological droughts. Vicente-Serrano (2006) used the SPI to analyse drought spatial patterns as a function of the time scales used in the index computation. For this, the SPI was computed at several time scales to detect soil moisture and hydrological droughts. Other studies analysing the effect of the accumulated period are Vicente-Serrano and López-Moreno (2005) and Edossa et al. (2009).

There is a need to better understand droughts at the current time as well as in the future. For this purpose, the current regional modelling tools must first be evaluated. The work presented here has two objectives:

- To analyse how RCMs characterise meteorological, soil moisture, and hydrological drought.
- To analyse how RCMs represent the propagation from a precipitation anomaly to a soil moisture and streamflow anomaly.

While the first objective aims towards contributing to drought representation analysis by RCMs, the second objective assesses how these models simulate drought propagation. This is a key issue for the understanding of drought that has not been fully analysed from a RCM perspective. In this study, each type of drought is characterised using standardized indices that define drought according to the variability in a given variable: precipitation (meteorological drought), soil moisture (soil moisture drought), and streamflow and total runoff (hydrological drought). The work carried out analyses three RCMs: i) the “Centre National de Recherche Météorologique” Regional Climate System Model (CNRM-RCSM4, Sevault et al. (2014); Nabat et al. (2014)), ii) the COnsortium for Small-scale MOdelling (COSMO) model in CLimate Mode (COSMO-CLM, Rockel et al. (2008)), and iii) PROMES (Castro et al., 1993; Sánchez et al., 2004; Domínguez et al., 2010). The reference data used are i) the "Système d’Analyse Fournissant des Renseignements Atmosphériques à la Neige" (SAFRAN) atmospheric analysis (Quintana-Seguí, 2015), ii) LSM offline simulations from the 3-layer version of the "Interaction Sol-Biosphère-Atmosphère" (ISBA-3L) (Quintana-Seguí et al., 2019) and the Organising Carbon and Hydrology In Dynamic EcosystEms (ORCHIDEE) models, iii) a simulation from the "Sistema Integrado de Modelización Precipitación-Aportación" (SIMPA) hydrological model (Estrela and Quintas, 1996; Ruiz, 1999), and iv) observed streamflow.

2 Area and study period

This study was carried out across mainland Spain, which is known to experience frequent droughts (Olcina , 2001). In addition, soil moisture deficits in spring across southern Europe favour drought propagation and heat waves across northern Europe (Vautard et al., 2007; Zampieri et al., 2009), which makes this type of study even more necessary. The time period has been limited to the availability of RCM simulations and observations: from 1989 to 2008 for the meteorological and soil moisture drought and from 1989 to 2005 for the hydrological drought.

Precipitation across mainland Spain is complex (Serrano et al., 1999) and highly influenced by relief. The main climatic regimes are oceanic and Mediterranean. However, a semiarid climate or even a desert-like climate can be identified in the southeast (Aemet, 2011). In general, Spain is a semi-arid region and is not densely vegetated. As a result, soil moisture displays a large annual cycle. From a hydrological point of view, there is a strong dependence of the main rivers on the precipitation generated in the nearby relief and the resulting runoff. An example is in the Ebro Basin and the Pyrenees. In addition, the impact of the anthropic effect must be taken into account because there is a wide network of dams and river canals that, in some cases, operate between basins.

According to Sousa et al. (2011), drought in Spain has increased in severity and frequency. Although precipitation does not show significant annual trends, observations show a reduction in spring and summer (de Luis et al., 2010) as well as an increase in the number of consecutive dry days (Turco and Llasat, 2011). Both aspects have an impact on soil moisture drought, which is also affected by an increase in annual and seasonal temperatures (del Rio et al., 2011; Kenawy et al., 2013). This rise in temperature increases the atmospheric demand (Vicente-Serrano et al., 2014) and thus evapotranspiration, reducing the soil’s water content. For hydrological drought, we must also consider the advance in the thaw date and a thinning of the blanket of snow in mountainous areas, such as in the Pyrenees (Morán-Tejeda et al., 2013), which affect streamflow and increase this type of drought. However, it should be noted that snow melt can affect streamflow and thus hydrological drought in different ways depending on its timing (Van Loon et al., 2010).

3 Datasets

This section describes the RCMs analysed (Sect. 3.1) and the reference products used (Sec. 3.2).

3.1 Regional climate models

In this study, drought representation and propagation in three RCMs are analysed. RCM simulations were downloaded from the Med-CORDEX database, which is a contribution to the Coordinated Regional Climate Downscaling Experiment (CORDEX, Giorgi et al. (2009)) focusing on the Mediterranean region (Ruti et al., 2015). The criterion used to select the models was that each one used a different surface scheme and therefore represented physical processes related to precipitation, soil moisture, and surface and sub-surface runoff in different ways. The three RCMs selected are listed in Table 1 and described below:

- The CNRM-RCSM4 (Sevault et al., 2014; Nabat et al., 2014) is a RCM developed by the CNRM. It includes the regional climatic atmospheric model "Aire Limitée Adaptation dynamique Développement InterNational" (ALADIN-Climate, Radu et al. (2008); Déqué and Somot (2008); Farda et al. (2010); Colin et al. (2010); Herrmann et al. (2011)), the 3-layer version of the ISBA LSM (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996), the Total Runoff Integrating Pathways (TRIP) routing scheme (Decharme et al., 2010), and the regional ocean model NEMOMED8 (Beuvier et al., 2010). Hereafter, it will be referred to as RS4.

- The COSMO-CLM (CCLM) model (Rockel et al., 2008) is the climate version of the COSMO model developed by the Goethe Universität Frankfurt (GUF). The surface scheme is a multilayer version of the Jacobsen and Heise (1982) two-layer model. Hereafter, it will be referred to as CL4.

- The PROMES model (Castro et al., 1993; Sánchez et al., 2004; Domínguez et al., 2010) was developed by the Universidad Complutense de Madrid (UCM) and the Universidad de Castilla-La Mancha (UCLM). It is coupled to the ORCHIDEE LSM (De Rosnay and Polcher, 1998; Krinner et al., 2005). Hereafter, it will be referred to as PMS.

All the RCM simulations are driven by the ECMWF Interim Re-Analysis (ERA-Interim) (Balsamo et al., 2012; Dee et al., 2011), which provides a global atmospheric reanalysis that starts in 1979 and is continuously updated in real time. In addition, it improves some important issues pertaining to ERA-40, such as the representation of the hydrological cycle. This reanalysis is performed by means of a data assimilation system based on a 2006 release of the ECMWF's Integrated Forecast System, IFS (Cy31r2), and uses a 4-dimensional variational analysis (4D-Var) with a 12-hour analysis window. The database has atmospheric and surface parameters with a temporal scale of 6 and 3 hours, respectively. The spatial resolution is 80 km, with 60 vertical levels from the surface to 0.1 hPa.

ERA-Interim is a well-known atmospheric forcing used in a large number of studies. For instance, Belo-Pereira et al. (2011) and Quintana-Seguí et al. (2017) have validated it across the Iberian Peninsula. However, biases in this type of forcing have a negative effect on LSM simulations, which can be corrected (Ngo-Duc et al., 2005; Weedon et al., 2011).

In this study, ERA-Interim is the driving data of the three RCMs analysed. In addition, it is also used to force LSM simulations used as a reference in the soil moisture drought analysis. Hereafter, it will be referred to as ERA.

Table 1. RCMs analysed in this study.

RCM Name		Surface Scheme	Driving Data
CNRM-RCSM4	RS4	ISBA-3L	ERA-Interim
COSMO-CLM	CL4	Multilayer	
PROMES	PMS	ORCHIDEE	

Table 2. Reference products used in the meteorological, soil moisture and hydrological drought analyses.

Drought Analysis	Product Type	Name		Comments
Meteorological	Analysis	SAFRAN (Low Resolution)	SLR	Spatial resolution: 30 km
				Temporal resolution: 1 h
Soil moisture	LSM	ISBA-3L	ISB	Simulation forced with SLR
				Simulation forced with ERA
		ORCHIDEE	ORC	Simulation forced with ERA
Hydrological	Hydrological model	SIMPA	SMP	Simulation using its own forcing
	Observations	OBS		Daily data

3.2 Reference products

This section is divided into three subsections to describe the products used as reference data in the meteorological (Sect. 3.2.1), soil moisture (Sect. 3.2.2), and hydrological (Sect. 3.2.3) drought analyses. The products are listed in Table 2.

3.2.1 Meteorological drought reference

SAFRAN is a meteorological analysis system (Durand et al., 1993, 1999) developed by Météo-France. It provides estimates of the following variables: precipitation, 2 m temperature, 10 m wind speed, 2 m relative humidity, and cloudiness, as well as modelled downward visible and infrared radiation following the radiation scheme of (Ritter and Geleyn, 1992). For this, an optimal interpolation algorithm (Gandin, 1966) that combines observations and a first guess is used. The first guess employed is ERA for all variables, except for precipitation, which is obtained from observations, and this is the reason why it has been selected as the reference dataset for the meteorological drought analysis. The meteorological station data belong to the Spanish Meteorological State Agency (Agencia Estatal de METeorología, AEMET) network. Precipitation is analysed by means of daily observations, while the remaining variables are analysed every 6 hours. The data are then interpolated hourly using different methods that depend on the variable. In Spain, SAFRAN was extended for a 35-year period (1979/1980 – 2013/2014) (Quintana-Seguí et al., 2017) and was implemented and validated over the Ebro Basin (north-eastern Spain) (Quintana-Seguí et al., 2016).

In this study, the standard version of SAFRAN, at 5 km resolution, has been regridded to 30 km resolution (Quintana-Seguí et al., 2019) to compare it with the RCM simulations as the reference in meteorological drought analysis and to force LSM simulations which are the reference in the soil moisture drought analysis. Hereafter, it will be referred to as SLR (SAFRAN Low Resolution).

3.2.2 Soil moisture drought reference

Offline LSM simulations are used in this study as a reference to analyse soil moisture drought because there is a lack of soil moisture data across mainland Spain that are suitable for studies that require a large spatial coverage. Internally, in RCMs, LSMs are bidirectionally coupled to the atmospheric model to simulate surface processes. However, when LSMs are run offline (forced by gridded databases), biases due to the atmospheric model and the coupling between the atmospheric model and the LSM are avoided. This makes offline LSM simulations good reference datasets to study drought. We selected three offline LSM simulations that use the same surface schemes employed by two of the RCMs analysed in this study.

The ISBA LSM (Noilhan and Planton, 1989; Noilhan and Mahfouf, 1996), developed by the CNRM, is composed of various modules that simulate heat and water transfer in the soil, vegetation, snow, and surface hydrology. This scheme has evolved using different approaches to model the soil. As a result, there are several versions that can be used. For this study, we selected the ISBA-3L (Boone et al., 1999), which considers a three layered description of the soil. It should be stressed that the ISBA-3L is limited by certain aspects. For example, underground water is not represented, and there is no horizontal water transfer. Most of the ISBA's soil and vegetation parameters are derived from the ECOCLIMAP land cover database at a 1 km resolution (Masson et al., 2003; Kaptue et al., 2010; Faroux et al., 2013), such as the cover types and soil texture. This database considers more than 550 cover types from all around the world. Its vegetation variability depends on the location, climate, and phenology.

The ORCHIDEE LSM (De Rosnay and Polcher, 1998; Krinner et al., 2005) was developed by the Institut Pierre-Simon Laplace (IPSL). It can be run in a stand-alone mode or coupled to the Laboratoire de Météorologie Dynamique (LMD-Z) General Circulation Model (Li, 1999), which was developed by the LMD in Paris. Hydrology is approached by means of a diffusive equation with a multilayer scheme. For this, the Fokker-Planck equation is solved considering a soil depth of 2 m distributed across eleven layers. The fine resolution is key to better model the interaction between the root profile and the soil moisture distribution at different depths as well as infiltration processes. In addition, ORCHIDEE includes sub-grid variability in soil moisture. Each grid box is divided into three soil moisture profiles with different vegetation distributions, but the same soil texture and structure that are obtained from the Zobler map (Post and Zobler, 2000).

In this study, three offline LSM simulations are used in the soil moisture drought analysis. Two of them use the 3-layer version of the ISBA model (one simulation was forced with SLR and another one with ERA), and the other simulation uses the ORCHIDEE LSM forced with ERA. Hereafter, the ISBA and ORCHIDEE LSMs will be referred to as the ISB and ORC, respectively.

3.2.3 Hydrological drought reference

For the hydrological drought analysis, modelled and observed streamflow data were used as references. Two issues should be stressed before explaining these datasets. The first is that the Med-CORDEX database does not provide simulated streamflow for any of the three RCMs, which would be the variable ideally suited for this study. In the absence of such data, it was decided to use modelled total runoff (hereafter referred to as runoff) corresponding to the sub-basins defined by a selection of gauging stations. We believe that this approximation is valid because we use a coarse time step, with a larger time propagation than the flow propagation. In fact, other studies use this variable to analyse hydrological drought (Vu et al., 2015; Meresa et al., 2016). The second issue is that Spanish basins are highly influenced by human management. However, RCMs do not simulate water management procedures but do simulate natural regime behaviour. Bearing these considerations in mind, only gauging stations satisfying the following criteria were considered:

1. Ninety-five percent data completeness during the study period; this assures that the monthly series of observations has few gaps.
2. Area greater than 10000 km^2; the analysis was limited to large areas because streamflow is approximated by runoff, which is likely to perform poorly in small basins considering the coarse resolution of RCM simulations.
3. A KGE between SIMPA and the observations greater than 0.5 for the consideration of a near-natural regime. Stations had to be as natural as possible and their corresponding basins large enough to be compared to a low-resolution RCM. This is difficult in Spain due to the high degree of human influence. A high KGE value between SIMPA (naturalized flow) and the observations would indicate near-natural regime behaviour. Therefore, we performed a sensitivity analysis testing different values, and 0.5 was a reasonable compromise between the near-natural regime and a sufficient number of stations for the analysis. It is true that this threshold does not represent a completely natural regime, and thus some human influence can be present. However, it allows a fair comparison of the RCMs and observations.

The first criterion was satisfied by 87 stations, the second one by 13 of the 87 stations, and the third one, and thus the final selection, by 8 stations. Fig. 1 shows the locations of these stations together with the relief and the river network. Table 4 contains their code, their area, and the basin to which they belong.

SIMPA is a Spanish acronym meaning Integrated System for Rainfall-Runoff Modelling ("Sistema Integrado de Modelización Precipitación-Aportación)" (Estrela and Quintas, 1996; Ruiz, 1999). It is a conceptually distributed hydrological model for water management developed by the Spanish Centre for Studies and Experimentation on Public Works (”Centro de Estudios y Experimentación de Obras Públicas", CEDEX). SIMPA provides estimates of the water cycle’s main components, such as precipitation, evapotranspiration, and river discharge, at a monthly scale in a natural regime. This regime is characterized by the free flowing of water, with no aspect unrelated to the environment (such as dams for water resource management) affecting it. Data are provided on a 1 km^2 grid. The model employs its own forcing, HIDRO (Quintas, 1996), which uses an observational dataset similar to that of SAFRAN.

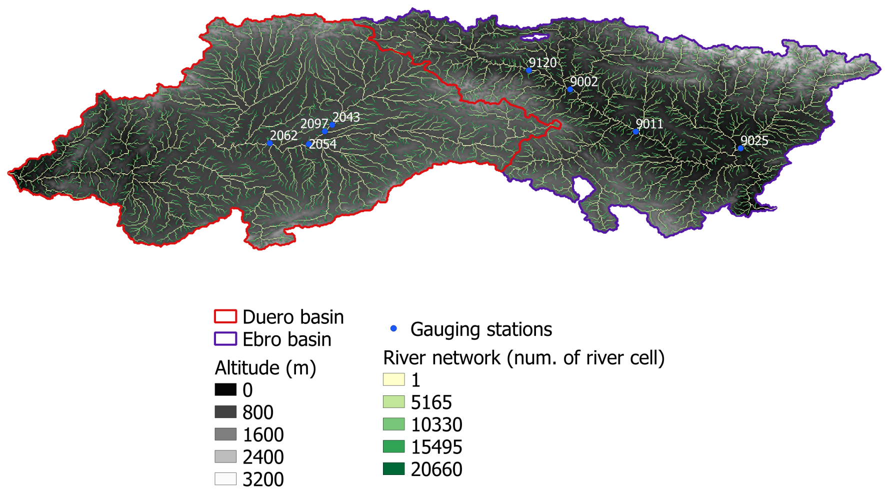


Figure 1. Map showing the relief, river network, and the locations of the gauging stations.

In this study SIMPA is used as a reference product for streamflow to analyse hydrological drought. Hereafter, it will be referred to as SMP.

Daily streamflow observations were also used as a reference in the hydrological drought analysis. These belong to the Spanish Ministry for the Ecological Transition, which provides data for basins comprising more than one region. Hereafter, they will be referred to as OBS.

4 Methodology

The methodology employed in this study is the same as that used in Quintana-Seguí et al. (2019). Therefore, the two studies complement each other, providing a wider analysis of drought representation by both LSMs and RCMs.

Drought can be characterized in several ways. Here, we used standardized indices that define drought according to the variability in a given variable. It should be noted that variability is a key aspect of drought analysis. For the meteorological and soil moisture drought analyses, we computed the SPI and a Standardized Soil Moisture Index (SSMI) using precipitation and soil moisture data, respectively. For the hydrological drought analysis we computed two indices: the Standardized Streamflow Index (SSI) using streamflow and the Standardized Runoff Index (SRI) using total runoff.

4.1 Drought index calculation

We followed the spirit of the SPI to compute the SSMI, SSI, and SRI. In these indices, the variable's time series is transformed from its original distribution to a normal one. The resulting values correspond to the number of standard deviations by which the anomaly deviates from the mean. Biases were not computed, as they are zero by construction. The computation was carried out using monthly data for all indices. In the case of the SPI, a time series of the accumulated precipitation from the previous n months (with n being the index scale) was also calculated to perform the drought propagation analyses. It should be noted that in the SPI methodology, data are fitted to the corresponding parametric distribution, which can be an issue in studies that standardize several variables, as in our case. To solve this problem, we used the non-parametric methodology described by Farahmand and AghaKouchak (2015).

On the one hand, meteorological drought representation by RCMs was addressed by comparing their SPI-12 time series with those of ERA and SLR. Using results from an accumulation period of 12 months is particularly robust due to seasonal reasons. Special attention was paid to differences in duration, severity and area. In addition, the temporal correlation of the RCMs' SPI-12 with that of ERA and SLR was computed to identify regions where drought representation improved, if any. On the other hand, the analysis of the RCMs' soil moisture and hydrological drought representation was performed through the calculation of Root Mean square Difference (RMSD) and the Pearson correlation coefficient (r) at a 95% significance level. We would like to stress that an RMSD equal to or greater than 0.5 often implies a change in drought category (i.e., from moderate to severe, for example) according to the SPI drought classification scale (McKee et al., 1993). To facilitate the Pearson correlation analysis interpretation, the guideline proposed by Evans (1996) was followed.

4.2 Meteorological drought propagation

The analysis of how meteorological drought propagates to soil moisture and hydrological drought is useful in hydrological resource management and allows the detection of similarities and differences in the way models address the physical processes that drive this propagation. The methodology employed to analyse meteorological drought propagation is based on Barker et al. (2016). The soil moisture memory of precedent precipitation will vary from one point to another depending on the location because soil moisture is controlled by different aspects regarding climate, soil and vegetation properties, such as precipitation, actual evapotranspiration, soil texture, stomatal resistance and root depth, among others. To determine the month scale at which the precipitation deficit propagates to a soil moisture deficit, we carried out the following analysis:

- Computed the standardized soil moisture index with a time accumulation of 1 month (SSMI-1).
- Computed the SPI with a time accumulation of 1 to 28 months (SPI-n_x).
- Identified the n_x scale that maximizes the correlation between SPI-n and SSMI-1.

The same methodology was employed to analyse how meteorological drought propagates to hydrological drought. For this, the SSI-1 was computed instead of the SSMI-1, and the SPI computation was performed using the areal mean of the basin precipitation defined by each studied gauging station.

4.3 Streamflow validation

The streamflow validation was carried out using the Kling-Gupta Efficiency (KGE) (Gupta et al., 2009). The optimal KGE value is 1, while negative values are sign of a model's bad performance.

5 Results

First, meteorological drought representation by RCMs is evaluated (Sect. 5.1). Next, soil moisture drought representation by RCMs is analysed as well as how the models address the transition from meteorological to soil moisture drought (Sect. 5.2). Finally, hydrological drought representation by RCMs and the propagation of meteorological to hydrological drought are analysed (Sect. 5.3).

5.1 Meteorological drought

In this section, we will focus on precipitation because its absence is the main cause of meteorological drought. The SPI is computed for the RCMs, ERA (driving data) and SLR (reference dataset). On the one hand, the comparison of the RCMs' SPI with that of ERA allows us to identify and determine to what extent these models reproduce the structures of their driving data. On the other hand, the comparison of the RCMs' and SLR's SPI shows to what extent the RCMs improve these structures, since the SLR dataset is based on observations.

5.1.1 Mean annual precipitation comparison

The first row of Fig. 2 shows the mean annual precipitation of ERA and SLR as well as the difference in mean annual precipitation between them. The rest of the rows show the RCMs' mean annual precipitation and their difference with respect to ERA (second column) and SLR (third column). All products show greater precipitation in the north-western and northern regions of the peninsula (exceeding 2000 mm/y) as well as over mountainous chains. The products also show that precipitation is lower along the main basin valleys (due to the orographic shadow effect) and minimal over the southeast, which is the driest region of the peninsula. For instance, precipitation across some areas of this region does not exceed 100 mm/y. The RCMs' mean precipitation spatial structures show similar behaviour as those from ERA and SLR. The fact that precipitation is high over mountainous chains indicates the strong influence of relief, which is key in the way water from precipitation is distributed. In fact, we would like to stress SLR's significant contrast in relief due to its use of data from AEMET's dense pluviometric network. This evidence indicates the complex spatial structure of precipitation in Spain.

Regarding the RCMs, RS4 and PMS show the greatest similarity and the highest contrast with CL4. When compared to ERA, both RCMs have higher precipitation, especially in mountainous areas. Modelled precipitation tends to overestimate precipitation compared to observations and ERA (Sylla et al., 2010). This reflects the addition of water in the form of precipitation, improving the RCMs' spatial distribution of precipitation with respect to the driving data. However, when RS4 and PMS are compared to SLR, precipitation is underestimated over some areas (valleys and the coastline). It must be borne in

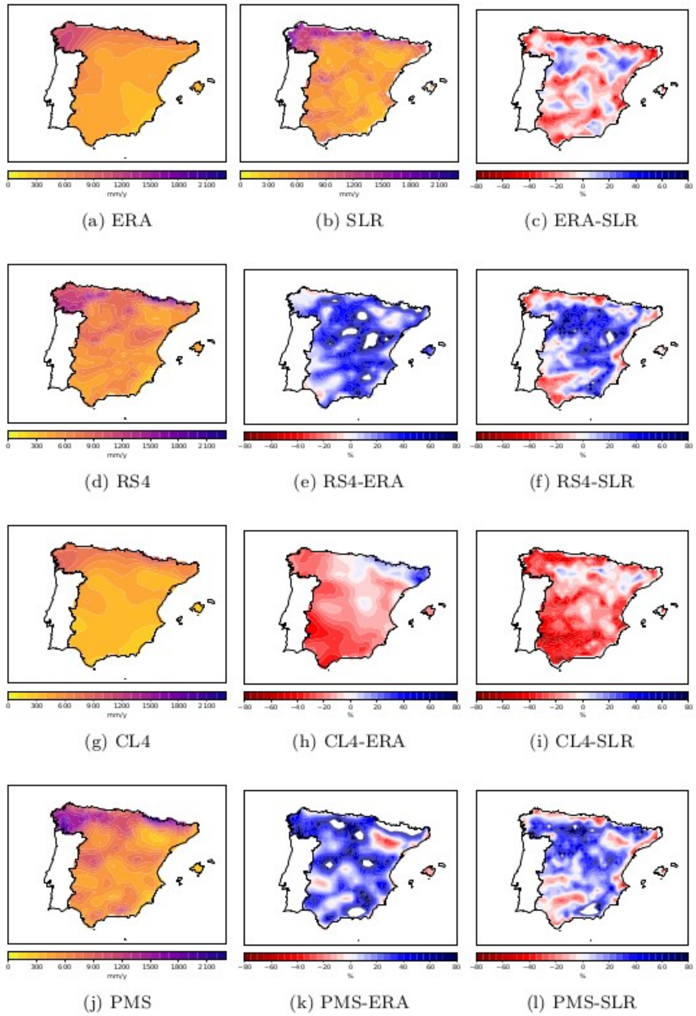


Figure 2. Mean annual precipitation across the study area between 1989 and 2008. Upper row: ERA and SLR mean precipitation and the difference between them. The rest of the rows: RCMs' mean precipitation and their difference with that of ERA and SLR.

mind that SAFRAN is mainly based on rain gauge information. The CL4 model is a different matter, since it underestimates precipitation for almost all of Spain when compared to ERA and SLR.

5.1.2 SPI comparison

Once the spatial distribution of precipitation in the peninsula is described, we can study the variability in the different products and thus their capacity to reproduce drought spells.

Figure 3 shows the time series of the SPI-12 calculated using mainland Spain's average precipitation as reproduced by ERA (panel a), SLR (panel b) and the RCMs (panels d, g, and j). The computation is performed for a time accumulation of 12 months.

ERA and SLR show several drought spells that occurred during the 20 years that comprised the study period (the most severe ocurred in 2005-2006). These spells coincide with those found by (Belo-Pereira et al., 2011) and appear in the RCMs' SPI time series plots as well. Therefore, RCMs are capable of reproducing these spells. However, differences in duration and severity can be observed. For instance, the duration of the spell that occurred in 1992 and 1993 was 21 and 22 months according to CL4 and PMS, respectively. However, it lasted 19 and 17 months according to SLR and ERA, respectively. Another interesting result is found in the spell that took place in 2002. CL4's mean severity is similar to that of ERA. However, the mean severity of both RS4 and PMS is in better agreement with that of SLR than with their driving data. Other information that can be extracted from these results is the timing of drought between the RCMs and their driving data and reference data. For example, the RCMs, ERA, and SLR agree that the spell that occurred between 1994 and 1995 started in May 1994 and ended in December 1995. The PMS model indicates the end of the spell occurring a month before the rest (November 1995). The spell between 2004 and 2006 started in November 2004 according to SLR, ERA, and PMS, which show similar durations (ERA = 23 months and SLR and CL4 = 24 months). However, it started in January 2005 according to RS4 and CL4 and had a longer duration: 27 (RS4) and 25 (CL4) months. In a previous study, a spurious trend in ERA was detected (Quintana-Seguí et al., 2019). This can be observed in Fig. 3c, where the difference between the SPI-12 time series of ERA and SLR is represented. However, the differences between the RCMs and SLR SPI-12 time series show that these models do not drag this trend.

To deepen the analysis of the spatial structure of meteorological drought, monthly SPI-12 maps were computed. The comparison of these structures, as shown by the RCMs, with those of their driving data and the reference dataset, provides more information about drought representation by RCMs. For instance, the temporal evolution of the spatial correlation of the SPI-12 maps of the RCMs with ERA and SLR (not shown) indicates the similarity between the RCMs and their driving data and reality (as approximated by SLR), respectively. In the first case, RS4 most resembles ERA. Despite not showing the highest correlations, it has less variability and is therefore more robust. The correlations of CL4 and PMS with ERA are more variable, reaching values close to zero in some months, in which the spatial structure of drought is not captured. In the second case, RCMs are found to correlate worse with SLR than with ERA, as expected. It should be stressed that RS4 also shows better correlations than the other RCMs when these are compared to SLR. Thus, out of the three RCMs studied, RS4 deviates less from the driving data and most resembles the reference. The correlation between ERA and SLR shows some variability in its temporal evolution, especially since 2000. This is likely due to the effect of the spurious trend identified in Fig. 3. To complement the spatial structure analysis, Fig. 4 provides information about the difference in the percentage of area affected by drought (SPI-12 $<$ -1) between the RCMs and i) ERA (panel a) and ii) SLR (panel b). The differences are generally under 25%, slightly lower than those with respect to SLR. In general, the RCMs show similar behaviour during a drought spell, meaning that they all overestimate or underestimate the affected area. For example, all three underestimate the area in 1994, overestimate it in 1995 and underestimate it in 1996. The difference relates to the degree to which they deviate. On the one hand, in 1995, RS4 overestimates the percentage of area affected by drought by 20 %, CL4 by approximately 15 %, and PMS by less than 10 %. On the other hand, in 1996, PMSunderestimates this percentage by more than 30 %, while RS4 and CL4 underestimate it by 10 %. Another example is how the RCMs overestimate the area in 2000 and how they underestimate it

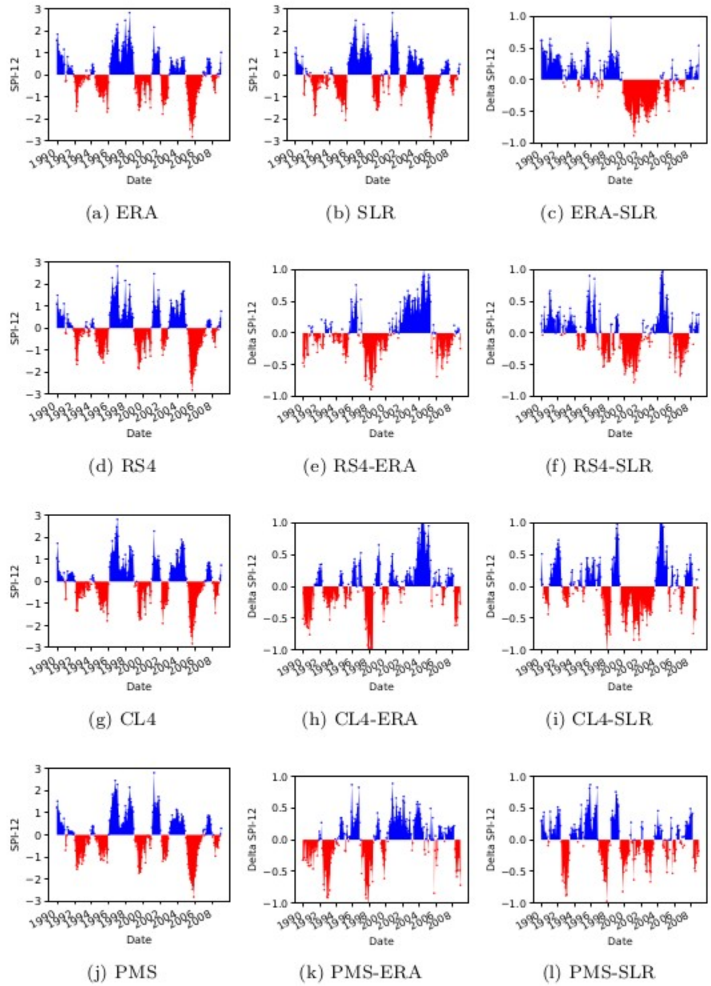
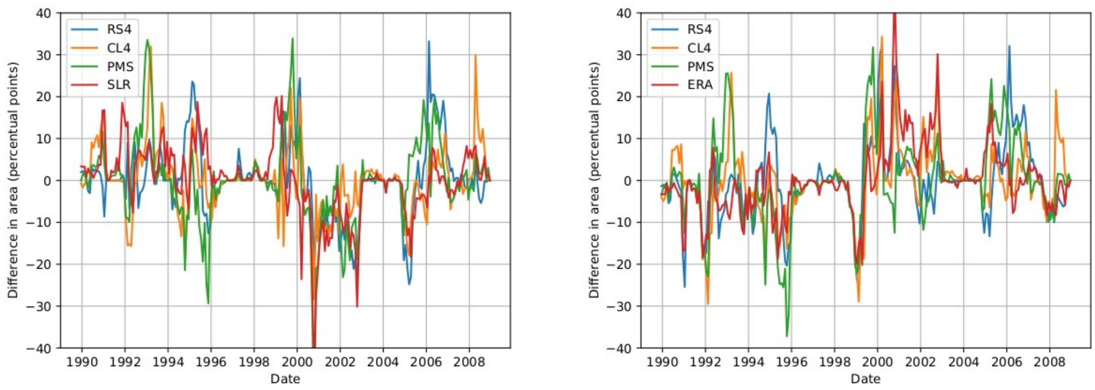


Figure 3. SPI-12 time series. First row: SPI-12 calculated with the spatially aggregated time series of mainland Spain precipitation, as reproduced by ERA and SLR, together with the difference between them. The rest of the rows: SPI-12 time series calculated with the spatially aggregated time series of mainland Spain precipitation, as reproduced by the RCMs, together with their difference with respect to ERA (second column) and SLR (third column).

between 2001 and 2003. RS4 is the RCM that shows the lowest percentage difference, which is consistent with our previous results.

Finally, Fig. 5 provides an idea of the spatial structures of drought representation. For this, the temporal correlation (Pearson) of the SPI-12 between the RCMs and i) ERA (upper row) and ii) SLR (lower row) is computed for each grid point. The correlations of the RCMs with ERA are above 0.8 in the south and worsen towards the north and the eastern coast, reaching 0.2. The Ebro Basin is the region showing the poorest values and thus the largest differences in drought representation between



(a) ERA (b) SLR

Figure 4. Differences in the proportion of area under drought (SPI-12 < -1) estimated by i) the RCMs and SLR with respect to ERA (panel a) and ii) the RCMs and ERA with respect to SLR (panel b).

the RCMs and ERA. Differences in this area are also identified in the map showing the correlation between ERA and SLR, where values are even negative. However, when the RCMs are compared to SLR (lower row), the correlations are higher across this basin. Consequently, RCMs improve drought representation across this region.

5.2 Soil moisture drought

In this section, the analysis focuses on models (Table 2). More precisely, it focuses on how they reproduce soil moisture drought (Sect. 5.2.1) and its propagation from precipitation to soil moisture (Sect. 5.2.2). Offline LSM simulations from the ISBA-3L and ORCHIDEE are used as references. We should bear in mind that in these simulations, soil processes do not impact the atmosphere, while the RCM simulations are performed in coupled mode and thus interact with the atmosphere.

5.2.1 SSMI comparison

The RMSD and the Pearson correlation coefficient (r) are calculated by comparing the SSMI from the RCM simulations and the LSM simulations. All mesh points and time steps are included in the comparison. Therefore, the results provide information regarding spatial and temporal drought structures. It should be noted that biases are not calculated because they are zero by construction (the mean of the SSMI is zero). The results are shown in Table 3, the table above corresponds to the RMSD and

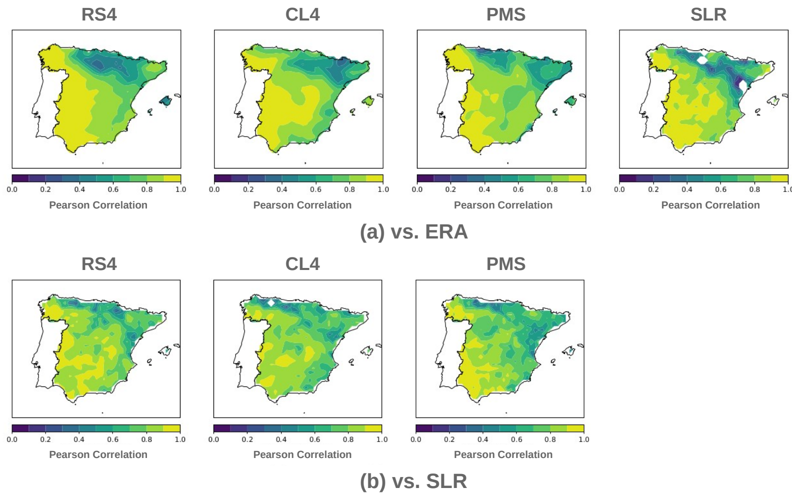


Figure 5. Map of the temporal correlation (Pearson) between the SPI-12 time series produced by i) the RCMs and SLR with respect to ERA (upper row) and ii) the RCMs and ERA with respect to SLR (lower row). Regions whose values are not within the colour scale are represented in white.

the table below corresponds to the r calculations. A colour scale consisting of a blue (largest similarity between models) to red (lowest similarity between models) gradient via white has been included to facilitate reading.

To put these results into context, we will consider the drought classification according to the SPI, which is divided into 8 categories from "extremely wet" (SPI = 2) to "extreme drought" (SPI = -2). A RMSD equal to 1 is a standard deviation of the index studied (in this case, the SSMI). In the framework of drought analysis, a value higher than 0.5 would imply a change in category (for example, from "slightly wet" to "moderately dry"). Therefore, the upper block of Table 3 shows that there is a change in drought category when comparing the RCMs with the reference offline LSM simulations, since the RMSD is above 0.5 (fourth to sixth columns). In addition, the three RCMs compared among them also represent soil moisture droughts of different categories (second and third columns), as expected.

Going into detail, we can observe some similarity between the RS4 simulation, which uses the ISBA surface scheme, and the ISB simulations. Compared to ISB, RS4 reproduces drought better than the other RCMs used in this study. However, this does not occur when the PMS and ORC simulations are compared, despite using the same surface scheme. In fact, RS4 and CL4 are, in general, more similar to ORC than PMS, according to the statistics. The SSMI comparison of the RCMs with both ISB simulations (fifth column vs. sixth column) shows very similar statistics. Discrepancies could be explained by the RCMs' land-atmosphere coupling and forcing effects.

Table 3. Comparison of the SSMI data from the RCM and LSM simulations. The upper block shows the RMSD, and the lower block shows the Pearson correlation (r).

RMSD	ERA-CL4	ERA-PMS	ERA-ORC	ERA-ISB	SLR-ISB
ERA-RS4	1.3	1.26	1	0.79	0.81
ERA-CL4		0.96	1.12	1.2	1.24
ERA-PMS			1.23	1.17	1.19
ERA-ORC				0.87	0.97
ERA-ISB					0.58

r	ERA-CL4	ERA-PMS	ERA-ORC	ERA-ISB	SLR-ISB
ERA-RS4	0.3	0.36	0.46	0.66	0.65
ERA-CL4		0.65	0.5	0.35	0.3
ERA-PMS			0.39	0.39	0.37
ERA-ORC				0.58	0.49
ERA-ISB					0.82

5.2.2 Propagation to soil moisture drought

n_x maps from Fig. 6 indicate the scale in months at which the correlation between the SSMI-1 and SPI-n is maximal and thus the temporal scale at which meteorological drought propagates to soil moisture drought. The first row shows RCM maps, while the second row shows ISB and ORC LSM (reference data) maps. The scale ranges from 0 to 28 months, with the dynamics of the model in regions with a yellowish tone slower than those in regions with a bluish tone.

The first row shows that the RCMs provide different results even though they use the same driving data, which indicates the predominance of model structure with respect to the driving data. This becomes more evident when a RCM is compared to the LSM that has the same surface scheme. For example, the RS4 and ISB maps show similar spatial patterns. These are very homogeneous, with scales that range from 1 to 4 months, implying that ISB reacts very quickly to precipitation. Another example is the comparison between PMS and ORC. Both models show greater heterogeneity than ISB, with scales from 1 to 20 (PMS) and 24 (ORC) months, highlighting the role of the continental surface. Finally, the CL4 behaviour is quite flat. The peninsula is divided into two areas, one over the north-west, where the n_x scale ranges between 6 and 12 months, and a larger

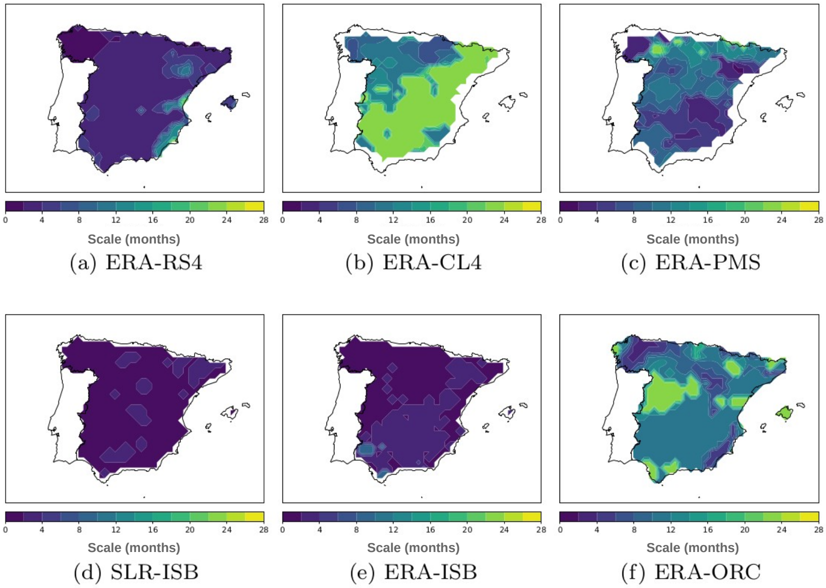


Figure 6. n_x Timescale maximizing the correlation between the SPI-n_x and SSMI-1 for the RCM and LSM simulations. Regions whose values are not within the colour scale are represented in white.

one with a fixed value of 20 months. It is interesting to note the similar spatial structures from the ERA-CL4 and ERA-ISB maps, indicating that soil moisture drought propagation by CL4 drags the same spatial structures as its driving data.

5.3 Hydrological drought

In Sect. 5.3.1, streamflow and aggregated runoff will be compared. Next, the RCMs' capacity to simulate hydrological drought will be analysed by comparing the SSI and SRI (Sect. 5.3.2). Finally, we will analyse the way in which RCMs reproduce meteorological drought propagation to hydrological drought (Sect. 5.3.3).

5.3.1 Streamflow and aggregated runoff comparison

Table 4 shows the KGE comparing RCM aggregated runoff with SMP and OBS as well as the comparison between SMP and OBS. All of these comparisons are performed at a monthly scale. Negative values, indicating poor performance, are marked in red. For the positive KGE values, a colour scale consisting of a blue (best performance between the RCMs and i) SMP or ii) OBS) to red (worst performance between the RCMs and i) SMP or ii) OBS) gradient via white has been included to facilitate reading.

The RCMs show KGE values that are negative or close to zero at many stations. Focusing on the positive KGE values, CL4 has the worst performance, since the values are below 0.5. Although RS4 is the RCM showing the highest KGE value (0.7

Table 4. KGE of the aggregated runoff simulated by the RCMs compared with the reference streamflow of the SIMPA model and OBS. Note that observations are affected by anthropic effects.

Basin	Area (km^2)	Gauging station's code	vs. SMP			vs. OBS			
			ERA-RS4	ERA-CL4	ERA-PMS	ERA-RS4	ERA-CL4	ERA-PMS	SMP
Duero	**41808**	**2062**	-0.28	0.25	0.21	-0.57	0.4	0.33	0.52
Ebro	**40434**	**9011**	0.54	0.05	0.28	0.61	0.14	0.43	0.52
Duero	**36570**	**2054**	-0.13	0.23	0.22	-0.44	0.37	0.35	0.56
Ebro	**25194**	**9002**	0.6	-0.01	0.33	0.7	0.1	0.51	0.5
Duero	**15638**	**2097**	0.15	0.31	0.55	0.13	0.36	0.59	0.82
Duero	**14283**	**2043**	0.23	0.29	0.57	0.23	0.34	0.61	0.78
Ebro	**12782**	**9025**	0.27	0.04	0.27	-0.13	0.19	-0.04	0.51
Ebro	**12010**	**9120**	0.52	-0.03	0.19	0.53	0	0.22	0.76

at station number 9002 for the comparison between RS4 and OBS), PMS performs better across both basins according to the average value.

An analysis comparing the temporal series (not shown) of the RCMs' aggregated runoff with the reference streamflow (SMP and OBS) shows that CL4 sustains summer flows, which is a positive aspect. This is not the case for RS4 and PMS, which have steeper recession curves. In addition, RS4 is found to overestimate streamflow peaks at stations in the Duero basin. Finally, we would like to note that RS4 and PMS show a different behaviour from that of the reference data at station number 9025 (which represents the Segre sub-basin). Both models overestimate a large number of peaks. We believe that this may be explained by the fact that the Segre sub-basin is nival.

5.3.2 SSI and SRI comparison

Table 5 shows the RMSD and the Pearson correlation coefficient, r, comparing the RCMs' SRI with SMP's SSI. A colour scale consisting of a blue (largest similarity between models) to red (lowest similarity between models) gradient via white has been included to facilitate reading.

The results are similar to those in Sect. 5.2.1, since the RMSD values are above 0.5 (which often indicates a change in drought category). Therefore, according to the SPI drought classification, the RCMs represent hydrological droughts of a different category from that of the reference dataset. Nevertheless, the RCMs show moderate positive correlations with SMP according to the guideline proposed by Evans (1996). We would like to note that the worst statistics are shown by station 9025,

Table 5. Comparison of the SRI from the RCMs with the SSI from SMP. The table shows the RMSD and the Pearson correlation (r).

Gauging station's code	RMSD			r		
	ERA-RS4	ERA-CL4	ERA-PMS	ERA-RS4	ERA-CL4	ERA-PMS
2062	1	0.82	0.98	0.49	0.62	0.47
9011	0.78	0.87	0.84	0.68	0.57	0.6
2054	0.99	0.84	0.97	0.5	0.61	0.48
9002	0.8	0.9	0.83	0.66	0.55	0.61
2097	0.99	0.91	0.98	0.5	0.54	0.47
2043	0.99	0.92	0.99	0.51	0.53	0.46
9025	0.97	1.17	1.07	0.49	0.24	0.36
9120	1.07	0.94	0.97	0.43	0.5	0.47

which is identified in the previous section as the station showing the worst performance. It is highly influenced by the effects of snow, which could explain the high RMSD and weak r values.

5.3.3 Propagation to hydrological drought

Table 6 shows the n_x values that indicate the monthly scale at which the correlation between the SPI-n_x and i) SRI-1 (RCMs) and ii) SSI-1 (SMP and OBS) is maximal. This can be interpreted as the temporal scale at which meteorological drought propagates to hydrological drought. To better understand these results and to what extent they reflect the propagation of a precipitation anomaly to a streamflow anomaly, a colour scale is included to indicate the strength of the correlation. It follows the guideline given by Evans (1996): very strong (yellow), strong (blue), moderate (white), and weak (red).

Opposite to Sect. 5.2.2, RS4 and PMS show very similar scales: means of 3 months for stations in the Duero Basin and 2 months (RS4) and 1 month (PMS) for stations in the Ebro Basin. However, CL4 provides larger scales, from 9 to 13 months (Duero Basin) and from 1 to 8 months (Ebro Basin). The difference in scales shown by the RCMs is an indicator of the relevance of model structure in drought propagation. This result is also obtained in Sect. 5.2.2.

The RCMs and SMP show higher n_x values and thus slower dynamics in the Duero Basin than in the Ebro Basin. This is in agreement with the n_x values obtained using the SSI-1 computed with OBS, in which the mean n_x values are 9 (Duero) and 4 (Ebro). Analysing these results, we can establish that the RS4 and PMS runoff responds quickly to precipitation anomalies. When compared to SMP and OBS, the monthly scales provided are in good agreement in the Ebro Basin but are too low in the

Table 6. n_x scale maximizing the correlation between the SPI-n_x and i) SRI-1 (RCMs) and ii) SSI-1 (SMP and OBS). Scales longer than 12 months are marked in bold. A colour scale has been included to indicate the strength of the correlations between the SPI-n_x and i) SRI-1 and ii) SSI-1 following the guide proposed by Evans (1996). The correlation ranges and the associated colours are i) very strong, 0.80-1.0 (yellow), ii) strong, 0.60-0.79 (blue), iii) moderate, 0.40-0.59 (white), and iv) weak, 0.20-0.39 (red).

Gauging station's code	RCMs			SIMPA	
	ERA-RS4	ERA-CL4	ERA-PMS	SMP-SMP	SMP-OBS
2062	3	12	3	9	9
9011	2	8	1	2	3
2054	3	9	3	9	9
9002	2	8	1	1	3
2097	3	**13**	3	8	10
2043	3	**13**	3	8	10
9025	2	1	1	2	8
9120	3	6	3	1	3

Duero Basin. In contrast, CL4 shows larger scales and behaves inversely to RS4 and PMS, since it is in better agreement with SMP and OBS in the Duero Basin.

Focusing on the strength of the correlations, RS4 (coupled to ISB) shows strong positive correlations at six of the eight stations analysed, indicating that precipitation has a significant role in streamflow variability. However, the correlations of CL4 and PMS with the SPI-n_x are moderate (even weak for station number 9025), which implies that there are also other factors driving this variability.

6 Discussion

This study provides an assessment of how RCMs represent meteorological, soil moisture, and hydrological drought as well as the way in which precipitation anomalies propagate to soil moisture and streamflow anomalies. This assessment was performed using standardized indices, which we believe are a good option for performing drought analysis. The reason for this is that they describe drought based on the variability in a given variable, and thus each type of drought can be studied using the variable that best suits its characteristics. In this work, four indices were computed: SPI (precipitation), SSMI (soil moisture), SSI (streamflow), and SRI (total runoff).

RCMs provide a good representation of meteorological drought. The results show that they are capable of reproducing the same drought spells as those detected by their driving data and the reference data. However, they differ in terms of an event's duration, intensity, and area, as expected. We have identified that RCMs improve drought representation with respect to the driving data in several aspects. For instance, the temporal evolution of the SPI-12 shows that the severity of some of the drought spells is closer to that of the reference data. In addition, they do not reproduce the spurious trend identified in the driving data, which could lead to a misrepresentation of the phenomenon. Finally, a temporal correlation analysis shows that drought representation is improved over the north-eastern region of the Iberian Peninsula, which is a known limitation of global analysis across Spain. These results are consistent with previous studies showing that RCMs provide a suitable representation of drought using drought indices across Spain (Barrera-Escoda et al., 2013; Maule et al., 2013; García-Valdecasas Ojeda et al., 2017).

Unlike the previous analysis, the results regarding soil moisture and hydrological drought representation show differences when RCMs are compared among themselves and to the reference data. The analyses are carried out using the RMSD and Pearson correlations, and the observed uncertainty corresponds, in most cases, to a change in the drought category (according to the SPI drought classification) of RCMs with respect to the reference data. These differences are expected if we consider the following aspects:

First, the reference data that are employed. LSM offline simulations are used as reference datasets for soil moisture drought analysis due to the lack of observations. In Spain, soil moisture data from the REMEDHUS network (Martínez-Fernández et al., 2013) and the Valencia Anchor Station (Coll-Pajarón, 2017) are available. However, these datasets are suitable for studies in which large spatial coverage is not an issue (such as model or satellite-derived data validation), which does not apply to our case. Remote sensing products could also be an option, but there are certain limitations that should be taken into account, for example, uncertainty sources, gaps in the data, and short time series (AghaKouchak et al., 2015). Escorihuela and Quintana-Seguí (2016) showed that different satellite products behave differently across a region representative of Mediterranean landscacpes (Catalonia in the northeast Iberian Peninsula). Therefore, using these products would add more uncertainty to the study. In addition, the retrieved soil moisture data correspond to surface soil moisture, and in this study, we considered root zone soil moisture. If the study was limited to the consideration of surface soil moisture, processes important to soil moisture drought would not be considered. Nevertheless, improvements in this discipline, as well as an increase in the length of time series, will convert these products into interesting alternatives for LSM simulations. Regarding the hydrological drought analysis, the observed streamflow in mainland Spain was used as a reference. However, the large number of dams and canals have a high anthropic impact on river systems, affecting the observed streamflow. Since RCMs do not take into account these effects, a simulation from the SIMPA model that provides streamflow data considering a natural regime is necessary as a reference dataset. It would be interesting to include these effects in RCM modelling to perform drought analysis using the observed streamflow as reference data. This would provide an idea of the anthropic impact on hydrological drought.

The second consideration is the use of LSMs. One of their main characteristics is that they simulate the water cycle by means of physical principles, which converts them into an interesting tool for studying soil moisture drought. However, an important drawback is that soil moisture is modelled differently in each LSM (Koster et al., 2009). This affects our analysis in two ways. First, the reference datasets will vary depending on the LSM chosen and its modelling approach. This is the reason why three soil moisture reference datasets were used in this study. Second, the RCM's soil moisture will also depend on the LSM modelling, as it is coupled to the LSM.

Third, the use of simulated total runoff to compute the SRI is due to the lack of RCM modelled streamflow data to compute the SSI. Hydrological drought representation and propagation are likely to be affected by this approximation according to the KGE values shown in Sect. 5.3.1. When compared to SMP, the KGE using total runoff is under 0.25 in almost half of the cases, which indicates poor performance. However, we would like to stress that PMS is the RCM that best approximates streamflow according to the KGE values.

Finally, the effects of RCM coupling with the atmosphere should be taken into account, since the soil moisture references are LSM simulations performed in an uncoupled mode and thus do not include atmospheric feedback.

We would also like to note the relevance of the time scale used to compute drought indices. According to García-Valdecasas Ojeda et al. (2017) and Bowden et al. (2016), the added value of the SPI is influenced by the accumulation period employed. This is interesting to consider because soil moisture and hydrological droughts have different scales of propagation, and differences are also found in the propagation analysis in Sect. 5.2.2 and 5.3.3.

The main objectives of this study are to evaluate drought properties and propagation in RCM simulations. Of the three RCMs analysed, RS4 shows the largest similarities with the reference data and deviates the least from its driving data in the meteorological and soil moisture drought analyses, while PMS shows the best performance in regard to hydrological drought. At this point, we would like to mention uncertainty, which is an important issue in this kind of study. Although the analysis was performed using only three models, these models provide different results in terms of drought indices and, especially, drought propagation. Adding more models would show the spread with more detail, but we believe that the differences among the three models are large enough to show that RCM developers should look at these issues and that RCM users should take them into account.

A key result of the study is the relevance of the models' physics, which prevails over the driving data. This is shown in the soil moisture and hydrological drought representation evaluation as well as in the analyses of drought propagation. In the latter case, the model's structure influences the temporal scale at which the variability in precipitation affects that of soil moisture and streamflow. For instance, in the analysis in Sect. 5.2.2, the spatial patterns of RS4 (coupled to ISB) and ISB are very similar and show that ISB, and thus RS4, respond too quickly to precipitation. The spatial structures of PMS (coupled to ORC) and ORC differ to a greater extent. The temporal scale of PMS is shorter than that of ORC, which may be due to coupling effects and to the fact that the precipitation extremes in PMS are too strong (Domínguez et al., 2013). Wang et al. (2011), in their analysis of climate change impacts on droughts, also highlight the fact that model structure is likely to contribute in an extensive way to different regional climate change projections.

The results obtained are coherent with those from Quintana-Seguí et al. (2019), in which the soil moisture and hydrological drought analyses also showed differences among LSMs. Therefore, both studies provide clear proof that improvements in modelling concerning soil moisture and streamflow are needed.

7 Conclusions

In the context of a changing climate, it is necessary to evaluate the evolution of extremes, such as drought. Understanding the processes involved is therefore vital. To do so, the current modelling tools must first be evaluated. The work presented here analyses how RCMs represent meteorological, soil moisture and hydrological drought and the propagation from a precipitation anomaly to soil moisture and streamflow anomalies.

It is concluded that RCMs provide added value to meteorological drought representation, minimizing possible error sources from the driving data and ameliorating its characterization over areas that are known to pose certain problems to global driving data products. However, soil moisture and hydrological drought representation by RCMs show uncertainties. This is mainly due to the relevance of model physics and its prevalence to the driving data. Similar results were obtained for the propagation processes, in which model structure was found to influence the dynamics of drought propagation, showing different temporal scales depending on how precipitation variability is formulated within the model.

RCMs are a suitable tool for meteorological drought studies but should be used cautiously for soil moisture and hydrological drought analyses. Improvements regarding soil moisture modelling and streamflow-related processes (natural and anthropic) should be performed to better characterise drought events as well as their propagation.

Some prospective studies pertaining to this work could be to relate the results obtained to real drought impact data to study the relevance of the uncertainties found in the soil moisture and hydrological drought analyses. In addition, the analyses can be extended by including more RCMs and other drought indices. On the one hand, using more models would increase the information about drought simulation at a regional scale but also allow the identification of further improvements in LSMs. On the other hand, if the analysis is performed with other indices, we can study the effects that other variables and processes, such as temperature and evapotranspiration, have on droughts. Studies of seasonal effects on droughts would also be interesting because these effects play an important role in drought propagation. Considering the soil moisture drought analysis, a comparison could be performed using in situ soil moisture data over a given point. Finally, it would be interesting to analyse the added value of drought indices as a function of the time scale used and how this may affect drought representation and its propagation.

Data availability. The forcing datasets and driving data used in this study can be accessed from their original source: ERA-Interim: https://www.ecmwf.int/en/forecasts/datasets/archive-datasets/reanalysis-datasets/era-interim; the SAFRAN dataset for Spain is available for research purposes from the Mistrals-HyMeX database (Quintana-Seguí, 2015). The RCM simulations were downloaded from the Med-CORDEX database: https://www.medcordex.eu/. The ORCHIDEE and SURFEX LSM simulations were produced for this study but can be reproduced using the corresponding release of the models: https://forge.ipsl.jussieu.fr/orchidee (release no. 4676); SURFEX: https://www.umr-cnrm.fr/surfex/spip.php?rubrique. Finally, the observed and modelled streamflow data from SIMPA can be accessed from the Spanish Ministry for the Ecological Transition website: https://www.miteco.gob.es/en/cartografia-y-sig/ide/descargas/agua/default.aspx

Competing interests. The authors declare that they have no conflict of interest.

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