**Author response to manuscript review**

HESS Discuss, 8, 7873-7918.

*Title:* Understanding climate processes in the Murray-Darling Basin: utility and limitations for natural resources management

*Authors:* Gallant, Kiem, Verdon-Kidd, Stone and Karoly

We thank the reviewers for their constructive comments and agree with the broad criticism that the paper in its current form is not focused enough for the natural resource management community.

We have alleviated this major criticism by re-writing sections of the introduction, and re-writing/re-structuring much of section 5. Specifically, we have introduced a qualitative framework for NRM in Section 5 that breaks down a climate event into its basic characteristics and compares these to those features that are similar to known mechanisms causing climate variations. This helps to isolate the potential causes of particular climatic events in the Murray-Darling Basin and we apply the 1997-2010 drought to this framework. Fundamentally, the framework was implicitly applied in our previous version of Section 5, but it was not explicitly broken down into simplified elements.

It is important to note that our framework will not provide definitive answers – nor will any other until the key uncertainties and knowledge gaps mentioned in our paper are addressed. However, it allows the user to qualitatively estimate the likelihood of a cause of a climatic event. We stress that this framework is not intended to be a decision-making tool – only to better focus understanding and assist in identifying knowledge gaps.

The framework breaks down a climatic event into its fundamental components, isolating i) spatial signatures, ii) temporal signatures and iii) small-scale evolution. Spatial information identifies the regional coverage of the event, including where it occurred and over what size area. Temporal signals identify the duration and length of the event, including any seasonality or recurrence. For example, a single season might experience an extreme climatic event but this may reoccur for multiple years. Small-scale evolution deconstructs the event to isolate smaller features. For example, the make-up of the daily rainfall distribution causing a seasonal anomaly – is the deficit due to a lack of rain days, or heavy rainfall events? Small-scale evolution also includes assessing changes in weather systems.

A complete manuscript has been uploaded that includes changes we have made in response to the reviewer comments. Responses to the major and specific comments from each reviewer are presented in the text below but have not been highlighted in the attached manuscript to ensure readability. Note the major changes are to the introduction and Section 5.

**MAJOR CHANGES:**

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| *REVIEWER COMMENT* | *RESPONSE* |
| The thing that is really missing, and would be an excellent contribution to the literature, is to explain to natural resource managers (e.g. hydrologists, irrigation managers, farmers, etc) why climate scientists use all these (ever growing number of) indices. | The following paragraph has been included in the introduction:  However, increasing the body of knowledge has the potential to be confusing for NRM. For example, the climate science community has identified a number of physical processes that influence variations in the MDB hydroclimate, which are often relayed to the NRM community as climate indices (i.e. simplified metrics of these atmosphere-ocean processes). Unavoidably, the number of these indices, and opinions as to what is important and what is not, increases as more research is conducted, adding uncertainty and complicating the information for those relying on it for risk assessment.  Also, two new tables are included to succinctly summarise various characteristics of some climate processes have been included (see Tables 1 and 2). |
| While the sub-title of the paper is ‘limitations for natural resources management’, the authors do not really examine how the understanding (and lack thereof) of climate drivers may limit natural resource management. | It is noted that there was never any intention to investigate the specific limitations for natural resource management practices in terms of policy and decision-making as this is far outside the area of expertise of the authors.  The limitations for natural resource management essentially stem from the large uncertainties in climate information. This issue is given renewed focus in the adapted Section 5. However, given its limited discussion, we have changed the title of the paper and removed the word “limitations”. |
| While the importance of the dipole in the IOD may be debatable, the importance of the Indian Ocean on southern MDB rainfall is not, and this should be stressed. Secondly, the state of the IOD appears to follow on from the previous ENSO state. Thus the importance of the IOD may vary depending on the ENSO that spawned it. | We agree that there is a definite influence of the Indian Ocean on the MDB climate. We believe we address this sufficiently in the text, including the issue that some studies have shown that it is dependent on the “type” of ENSO that spawned it (see references to Fisher et al. [2005] and Webster et al. [1999] in the text). However, as outlined in the specific comments section below, we have included the following sentence at the end of the major paragraph that discusses this issue:  We stress that, on the balance of current evidence, the Indian Ocean does play a role in regulating the MDB hydroclimate but it is likely that this role is as an intermediary driver only. What is in question is the modulation via an east-west dipole (i.e. IOD) mechanism and its dependence on or independence of the Indian Ocean teleconnections from ENSO. |
| I am surprised that the authors did not mention that the IPO has been in a positive phase for the past decade, potentially being one of the drivers of the Millennium Drought. They do however address this in Section 5. | As noted by the reviewer, this is addressed in Section 5 as this is where we examine the potential, specific causes.  In the new Section 5, this is discussed a little more explicitly as our qualitative framework identifies the IPO as a possible cause. |
| The authors state that global climate model projections do not show consistent changes in rainfall across the MDB. While this may be true of the MDB as a whole, the global climate models do project drier conditions across the southern Murray-Darling Basin, and particularly Victoria with the vast majority of models agreeing on a drying trend across the far south-east of Australia. This is seen in the outputs of both the Murray-Darling Basin Sustainable Yields Project and the Tasmania Sustainable Yields Project (http://www.csiro.au/partnerships/SYP.html). | A sentence acknowledging this fact has been included at the end of the paragraph describing model projections for the MDB:  One regional exception is the southern MDB, for which many climate models consistently project drying. However, the magnitude of this drying varies considerably between models [*Chiew et al.*, 2008] and the dynamical mechanisms behind this drying have not yet been identified. |
| Some of the paper appears to be written towards the broad non-scientific group of NRMs and as such minimises jargon (e.g. no mentioning of orographic dominance when first mentioning main rainfall drivers, lack of mention of ‘non-stationarity’ and reference to Milly et al (2008) pg 7875 par 4, ‘Ecohydrology’ on pg 7896 line 15, and ‘teleconections’ in section 3.3) yet I’m not convinced of the utility of this paper for this group even with minimised jargon. If the science community is then going to be the main audience then technical jargon should be used. I think the Authors need to clearly define the target audience (i.e. are they water managers, biodiversity, forestry etc.), and focus the paper to the needs of this audience through discussion addressing risk, uncertainty and management issues associated with the science raised in the paper. | We have revised much of the introduction to be targeted at natural resource managers. We have defined whom we are targeting, which includes groups such as water resource managers, agriculturalists and biodiversity managers.  Furthermore, we have refined the paper as having two broad objectives for these groups.  This amended version of our revised introduction (which is available in the revised document with tracked changes upload with this response) describes these two objectives:  …The collective research from these, and other, initiatives has provided invaluable information that is highly relevant to the NRM community.  However, increasing the body of knowledge has the potential to be confusing for NRM. For example, the climate science community has identified a number of physical processes that influence variations in the MDB hydroclimate, which are often relayed to the NRM community as climate indices (i.e. simplified metrics of these atmosphere-ocean processes). Unavoidably, the number of these indices, and opinions as to what is important and what is not, increases as more research is conducted, adding uncertainty and complicating the information for those relying on it for risk assessment.  Given the difficulties NRM might have utilizing the large amount of climate information available, this paper has two primary objectives. The first is to synthesize knowledge about the processes governing climatic variations across the MDB. This synthesis will distil up-to-date information in a concise form so that it may be interpreted more easily than compiling information from self-guided literature surveys. Murphy and Timbal [2008] have previously presented a synthesis of the major processes driving inter-annual and shorter time scale climatic variations in southeast Australia. While useful for the southern MDB, Murphy and Timbal’s [2008] paper did not describe the importance of these and other climate processes important to the northern MDB. Furthermore, information on decadal and longer-scale climate processes, interactions between climate drivers and interactions between climate and hydrological processes were not included in their review but are highly relevant for NRM.  As stated at the beginning of this document, we have identified a framework that essentially simplifies the steps that were intrinsically taken to identify potential causes for the drought in the previous version of Section 5. The framework simplifies these in a way that might be used by NRM groups. The framework then allows us to draw broad conclusions about the uncertainties associated with the outcome. |
| The review seems broad and I think there is value in reviewing scientific research on drivers of rainfall patterns in the MDB based on weather patterns and metrics like IOD, ENSO, SAM - these research areas have important interactions and could otherwise remain segregated. NRM managers could benefit from clarification of these indices yet I feel this paper does not succinctly do this. However, I do not feel that this paper can be published as a review paper – it just does not seem comprehensive enough to merit that. I guess the authors need to decide if they are trying to write a review paper on this problem, or present some new novel methodology or assessment that other researchers could benefit from, and modify their presentation accordingly. | We felt providing a broad synthesis outlining the processes governing climatic variations on a number of temporal and spatial scales would be more useful than a review going into detail that might not be required for NRM.  But to improve communication two new tables are included to succinctly summarise each of the climate processes, including their links to the defining characteristics of the drought such as seasonality, duration and spatial scale.  Furthermore, these tables form the basis for the broad framework presented in Section 5, described at the beginning of this document.  We feel these changes better focus the manuscript, providing valuable information and a broad methodology for NRM to isolate potential causes of climatic variations in the MDB. |
| There claims to be a focus on the northern MDB yet the only analysis in the paper is on the southern region, an area which has already been given much attention as recognised by the Authors. | We argue that this is not the case. All analysis performed by the authors with the exception of that surrounding Figure 5 applies to the whole MDB (e.g Figure 6 describes interactions between remote large-scale drivers, which is important for the whole MDB and Figure 7 describes combined impacts of ENSO and SAM across the whole Basin).  The reasons for the chosen domain in Figure 5 are explained in detail in the ‘specific comments’ section below. But, in short, the work is based on a previous study and the assumptions we rely on for the analysis are only applicable to this small domain in the southwest of the Basin. |
| Summary tables and figures distilling the important information are suggested to improve the message delivered in this paper, for example, diagrams showing the interactions between these phenomena – Taylor diagrams, interaction diagram/correlation plot, scatterplot matrices could be used to show the effects described in the text much more clearly. | See the second previous comment –two new tables are included to more succinctly summarize the climate processes for readers and are shown at the end of this document.  Minor wording changes have been made throughout to make the text more concise. |

**SPECIFIC COMMENTS:**

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| *REVIEWER COMMENT* | *RESPONSE* |
| page 2, lines 16-20. The first two sentences neatly sum up the importance of extremes. I would also add that “pushing the boundaries” can also drive adaptation responses for those that experience the extremes. | The following sentence was included at the end of the paragraph:  The impacts of these extreme events tend to force a somewhat *ad hoc* management response, driving both successful and unsuccessful adaptation (i.e. maladaptation) |
| page 7, lines 1-5. This sentence does not read correctly? Please rephrase. | The sentences have been refined and now read:  The importance of a particular type of weather system to seasonal rainfall totals is heavily dependent on the location. There can be substantial differences in the relative contributions from particular weather systems to seasonal accumulations over distances of several hundred kilometres only [*Verdon-Kidd and Kiem*, 2009].  The rainfall accumulations associated with different occurrences of the same type of weather system also vary… |
| page 15, lines 26-28. The model projections need a citation. Sun et al (2011 Water Resources Research, op cit.) is the most current citation here. | The citation has been included |
| page 22, lines 25-29 and Fig. 7. Fig. 7 presents a new and very informative result. However, it is hard to interpret properly without some measure of the relative frequency of the various combinations. A simple remedy is to add the number of occurrences. You have done this in Fig. 7 (the little n = 6, etc) under each plot. You need to describe those in the caption and discuss in the text. For example, both top and bottom rows are ~ 25% of the years each, leaving 50% for the middle rows, and so on. | The following explanation has been added to the caption for Figure 7:  The number, *n*, in each panel indicates the number of years from which the composite was computed, this is, the number of years in which the particular phases of ENSO and SAM co-occurred.  We have also included text surrounding this issue in the body of the paper, noting the small sample sizes. The three following paragraphs have been added describing obtaining statistical significance from a small sample and describing these results:  Note that the frequencies at which combined events occurred were small in several cases. So, producing composites from n randomised years tested the statistical significance, where n was equal to the number of years used to produce each composite (see Figure 7). Statistical significance was defined if the value of the composite being tested was larger/smaller than 97.5% of the randomised composites.  During combined positive SAM and El Niño, and negative SAM and La Niña, the rainfall anomalies in Figure 7 were statistically significant across most of the MDB (not shown). Interestingly, during JJA, the extreme phases of ENSO during neutral SAM had few statistically significant rainfall anomalies in the southern MDB. Thus, across the MDB, particularly the southern half, there is significantly enhanced drying and wetting respectively when positive SAM/El Niño or negative SAM/La Niña phases co-occur.  For combined positive SAM/La Niña events, the rainfall anomalies were not statistically significantly different in the southern MDB. However, when La Niña combined with negative or neutral SAM conditions it was statistically significantly wetter in this region, indicating that positive SAM may have some tempering effect. Similarly, for combined negative SAM/El Niño years, significant drying was limited to the far northeast of the Basin. However, for neutral SAM, significant drying extended across the northern and eastern two-thirds of the Basin and across most of the MDB for a positive SAM/El Niño combination. |
| Fig. 5 caption. Typo 6 lines down from top of caption. Delete “than”. Should read .... more (less) heavy rain days .... | The typo has been corrected |
| Include a sentence that stresses that even though we don’t think the IOD exists, we still think that the Indian Ocean is an important driver of SEA rainfall, it’s just that it’s an intermediary driver. | The following sentences have been added to the end of the relevant paragraph to stress this:  We stress that, on the balance of current evidence, the Indian Ocean does play a role in regulating the MDB hydroclimate but it is likely that this role is as an intermediary driver only. What is in question is the modulation via an east-west dipole (i.e. IOD) mechanism and its dependence on or independence of the Indian Ocean teleconnections from ENSO). |
| Include comment that climate models agree on drying in southern MDB (see MDB sustainable yields project) | The following sentence has been included at the end of the paragraph describing model projections:  One regional exception is the southern MDB, for which many climate models consistently project drying. However, the magnitude of this drying varies considerably between models [*Chiew et al.*, 2008] and the dynamical mechanisms behind this drying have not yet been identified. |
| Figure 5 caption: change word “annual” to 6-monthly i.e. April to October | The typo has been corrected |
| Discuss Figure 7 more, particularly in Section 5 | An extended discussion has been included. Please see comment above from another reviewer for the specific changes (five comments previously, on page 22, lines 25-29 and Fig. 7.) |
| The CSIRO and BoM reference should read ‘Climate Change in Australia’ not ‘Climate Change is Australia’. I would think that a reference to the website for this and the CSIRO MDB SY reference would be useful for the reader. | The typo in the reference has been corrected.  The websites for both Climate Change in Australia and the MDB Sustainable Yields Project are already given in paragraph 3 of the introduction (websites for other initiatives such as SEACI and IOCI are also in this paragraph). |
| Clearly define the northern and southern MDB and explain why there is less known about the drivers of rainfall in the northern part of the MDB compared to the south. | The northern and southern MDB has been explicitly defined, in line with previous work describing the ‘southern MDB’ or ‘southeast Australia’. Less is known about the region simply because it has not been given priority for examination by the climate science community.  So, the following has been included in the opening paragraph of Section 3:  Here, the northern and southern MDB are defined as the halves of the Basin north and south of the 33°S latitude line. To date, less focus has been given to understanding climate processes in the northern MDB by the climate science community and a synthesis has not previously been presented. |
| How representative is the Big Dry of other dry periods e.g. the Federation and World War II droughts? Would the drivers be the same? | This has been comprehensively addressed in the paper by Verdon-Kidd and Kiem (2009) (see references). We do not go into detail but just refer to their results within our paper. |
| The title says 'climate processes' but perhaps should be 'hydroclimatic processes' as the focus is predominantly on drivers of rainfall, not on other climate variables such as pressure, wind, temperature etc. | The title and appropriate section titles have been amended to ‘hydroclimate’ |
| Figure 4 should be explained more clearly both in text and in caption. | The explanations of the weather systems in Section 3.1 have been refined with specific references to Figure 4 throughout the text. The caption has also been amended and reads as follows:  **Figure 4.** The key weather systems that affect the Murray-Darling Basin during the austral (a) summer (DJF) and (b) winter (JJA). The southern half of the Basin is primarily affected by extra-tropical systems and receives the majority of its annual rainfall during the cooler months (May–October). The northern half of the Basin is primarily affected by tropical systems and interactions between tropical and extra-tropical systems and receives the majority of its annual rainfall during the warmer months (November–April). The systems that tend to suppress rainfall are shown in red. |
| SAM is not given the same level of detail as other synoptic drivers in Section 3.1. Is there are reason for this? | There is little new information available on the effects of the SAM since the Murphy and Timbal review. To limit overlap we only included a brief description of the impacts of SAM on the MDB, including the northern sections.  There is a sentence at the beginning of Section 3 that explains that only new information is provided and readers are directed to the Murphy and Timbal review for a more comprehensive summary. |
| Section 3.2 does not identify the duration and frequency of the events outlined. | The duration, frequency of interannual drivers is not explained in detail as it contained too much overlap with Murphy and Timbal (2008).  We have included a sentence in the opening paragraph of Section 3 explaining that all this information can be found in the Murphy and Timbal review. |
| Page 7884 line 28 – why summarise section 3.1 (intra-annual) in section 3.2 (inter-annual)? Section 3.2 also describes meteorological phenomena that affects the MDB. | This is not a summary of Section 3.1, which describes the weather systems themselves and how they are climatologically (on average) related to the MDB climate. Rather we are saying that the characteristics of the weather systems described in 3.1 (e.g. the number of systems etc) have inter-annual flucuations, which, in turn (and unsurprisingly) regulate annual rainfall.  The opening sentence has been changed to clarify this and now reads:  The weather systems described in Section 3.1 regulate inter-annual variations in MDB rainfall as their frequency, duration and intensity changes from year-to-year. |
| A key novelty of this paper identified by the Authors is the focus on the northern MDB yet Section 3.3 focuses on the South | To our reading, Section 3.3 does not focus on the south. There is no mention of the southern MDB in this section.  Section 3.3 gives descriptions of decadal drivers for “eastern Australia”, which includes all of the MDB and the results can be broadly generalized as such. We have clarified that eastern Australia includes the MDB, but have made no other changes. |
| Pg 7888 line 1 – the uncertainty in climate model problems is oversimplified here – the value of the statement “uncertainty must be addressed” is not very high without suggesting techniques to deal with this uncertainty. Consider rewording to portray the idea expressed in line 7 on page 7902 “it is unclear how we can simulate climate processes that we do not yet understand.” | Text has been inserted surrounding this issue. See the three paragraphs in Section 5 beginning with starting with:  The most obvious source of uncertainty is that there are numerous aspects of the climate system that are still not well understood and probably many more that are yet to be identified...  (Pages 38-40 of manuscript attached to this document) |
| Suggest that analysis in Fig. 5 be expanded to more than 7 stations and stations in the northern region. Is there a reason that all of these stations are in the southern MDB? | These are high-quality rainfall stations that are in a domain identified by Pook et al. (2006). In that paper, Pook showed that 80%+ of heavy rainfall days (>25 mm/day) in this domain are caused by cut-off low-pressure systems. Thus, investigating heavy rainfall days in the same domain allows us to draw the probable conclusion at the end of the paragraph:  The results here suggest that all three major drivers of interannual climate variations in the region partially regulate rainfall by changing the frequency of heavy daily rainfall events, which in turn are likely to be via modulation of the frequency of cut-off low pressure systems.  The two previous paragraphs describe this and why only these stations are used. As it seems this is not clear, we have amended the paragraph that introduces this section for clarification. It now reads as follows:  We present analysis in Figure 5 demonstrating the connections between climate processes operating on inter-annual and daily time scales. *Pook et al.* [2006] found that at least 80% of April–October heavy rain days (defined as days with accumulations above 25 mm) were associated with cut-off low-pressure systems in a domain covering the far southwest MDB. They also showed that cut-off low-pressure systems strongly modulate inter-annual rainfall there. Given that Section 3.2 outlined the modulation of inter-annual rainfall in the MDB by ENSO, SAM and the Indian Ocean, a logical hypothesis is that these remote drivers partially act by modulating the number of cut-off low-pressure systems that influence the region. This influence was examined here by using heavy rain days as a proxy of cut-off lows. |
| Page 7890 line 21, is there proof for this statement? | Please see the above comment. We argue that our results show proof for this with the caveat that we are assuming that heavy rain days are a reasonable proxy for cut-off low pressure systems. We argue in the text that they are, given that 80%+ of heavy rain days are associated with cut-off lows over the same period. |
| Page 7895 line 24 – the effect of climate change on these drivers may be very important. More than one sentence should refer to this. | This is included in the extended discussion on uncertainty in model projections in Section 5 – see the paragraph two comments previous. |
| Pg 7897 lines 11-13 what does this mean? Should it be proportional and not inversely proportional? | Yes, this is a mistake in the text and has been amended to read “…the certainty of our attribution is proportional to our understanding…” |
| Rather than just concluding things are uncertain, a discussion on further relevance to policy or management – i.e. how to manage this uncertainty: perhaps refer to some adaptive management papers, which explicitly incorporate uncertainty. | In the revised Section 5, we present a simplified framework that might be used by NRM and we discuss the implications of uncertainty in climate science. However, the intention of the paper is not to provide discussion on how NRM might manage uncertainty as we feel it’s outside the scope of the paper. |
| I found the writing style of using contrasts in parentheses such as “hot (cold) ... leads to ... increase (decrease) ...” very distracting. A focus on the important results (i.e. if the focus is on droughts only talk about reductions etc.) would improve text flow. | All instances have been changed. |
| Pg 7901 typo line 22. Repeat ‘to’ should be removed: “some simple analysis to highlight” | Typo has been corrected |