

May 15, 2018

Dear Professor Sivapalan,

Thank you for the opportunity to revise and resubmit our manuscript “On the social dynamics of moisture recycling.” We are pleased to hear that the revisions were well-received by the Referees and yourself. We have made the changes suggested by the Referees, and where we did not change, we explained our rationale. We indicate each original comment of a Referee with the prefix ‘RC’, and the Author Comment with ‘AC’.

I hope that the revised manuscript meets your expectations for Earth System Dynamics, and I look forward to your decision.

Warm regards,
Patrick Keys on behalf of co-author

REFEREE #1 (ANONYMOUS)

RC1: I found that the authors have put substantial additional efforts and thoroughly revised the manuscript considering all comments provided. Key questions driving the study have been added, both the quantitative and qualitative aspects of the study have been clearly highlighted, and all other comments have been addressed. Overall, the revised manuscript reads very well. I have only a few minor comments for the authors.

AC1: Thank you for the response. We will address your comments below

RC2: Perhaps I overlooked this in the previous review or I missed something in the revised version, but I wonder if there was a basis for the use of 1mm for boundary demarcation. In the current version, it is noted that the authors followed Keys et al. (2014); further elaboration would be appreciated.

AC2: Thank you for pointing this out. The basis for the 1mm boundary in this instance was to have a 'physical' boundary that was meaningful, primarily in the sense that common rain gauges have a lower limit of 1mm. Thus, theoretically, a region that contributes 1mm of rainfall is an approximate lower limit for what might be detectable in terms of change on common rain gauges. We will highlight this more clearly in the text where we discuss the 1mm boundary, so that our rationale is clear.

RC3: At numerous instances, the authors discuss policy relevance. For example, the text around lines 22-25 in page 17 and lines 7-10 in page 18. It is still unclear to me about how moisture recycling has been used in policy making/implementation. In particular, the authors note that, in regions with rule-of-law, evaporation is used in government regulations and policies. Could the authors elaborate this further and/or provide some examples/references about where and how this is done?

AC3: Thank you for this comment. We were evidently unclear in the text regarding policy relevance. To the best of our knowledge moisture recycling has not been used in policy making/implementation. Previous work has hypothesized approaches to moisture recycling governance, but we are unaware of explicit moisture recycling policies. We will make this distinction more clear.

REFEREE #2 (Paul Dirmeyer)

RC: The revised manuscript is much improved, and much much easier for the reader to follow. The reorganization of the manuscript has made the message much clearer and better serves the intent of the authors. Table 1 greatly aids readers in understanding the terminology used - few if any readers will be well versed in all of these terms, as you are bringing together concepts from (previously) disparate lines of research. Likewise, the new version of Fig 1 is a big improvement. Also, I appreciate the added specific examples that are given throughout Section 4 now - very helpful for comprehension.

All-in-all the manuscript is now of high quality - I suggest only minor revisions (mostly technical but a couple more substantial) based on the specific comments below. All comments below reference pages and line numbers in the marked-up version of the manuscript that accompanied the responses to reviewers.

AC: We very much appreciate the positive feedback from the Referee. We have made the suggested changes that you highlight below, and where we did not we explain our rationale.

Specific comments:

RC1: P2 L16: The term "unpacking" is informal, colloquial jargon; "understanding" would be a better choice.

AC1: Agreed, we have made this change.

RC2: P2 L27: "unexploredThese" needs a period and space in between.

AC2: Thank you, this text has been removed.

RC3: P3 L5: change "have" to "has"

AC3: Thank you, this has been changed.

RC4: Table 1: Next to "Social-ecological systems" put the abbreviation "(SES)" as it is used in the text.

AC4: Thank you, we have added this.

RC5: P6 L3: delete "similar"

AC5: Thank you, this has been changed.

RC6: P9 L7: "grey literature" is also informal and a bit pejorative. Using "non peer-reviewed literature" may be a better choice.

AC6: Thank you for the comment. We were not aware this can be interpreted as pejorative. This has been changed.

RC7: Fig 2: This appears to be a glitch only with this figure as it does not appear in Figs 3 and 4, but there is a blue background to panel (b) that makes the labels unreadable.

AC7: This is only present in the 'tracked changes' document. Not in the revised LaTeX file. We have made certain that the figure is normal, and readable, in the final LaTeX and PDF files.

RC8: Fig 2: In panel (d), what does a negative value for "malnourished children" mean? The whisker goes to -20.

AC8: This is a mistake and should of course not go below 0. We have fixed this. We have also made sure that there are no other such errors in the other files.

RC9: Fig 2 caption: Change "between country and" to "between the country and its".

AC9: Thank you, this has been changed for all figure captions.

RC10: Figs 2-4: Panel 3 in each, it is hard to digest this information as presented. I think it would help to order the categories on the abscissa by their source values (blue bars), from largest to smallest.

AC10: Thank you, this is a great idea. We experimented with different ways to present this information. It is not perfect, since the sorting of anthromes for the source areas is not the same as the same as sorting the anthromes for the sink. However, I think the sorted anthrome graphs are somewhat easier to interpret.

RC11: P12 L3: "kids" is informal; say "children". Also, change "evaporation key sources" to "key sources of evaporation".

AC11: Agreed on both counts. This has been changed.

RC12: P13 L19-20: "associated changes in near-surface meteorology"; of what sort? Please give specifics here.

AC12: Thank you for this comment. We have more closely read the referenced article, and we mis-attributed their findings. They quantified changes in NDVI, and *hypothesized* changes and suggested implications for atmospheric processes. We've adjusted our statement accordingly.

RC13: P14 L9: Delete redundant "from".

AC13: Thank you, this has been changed.

RC14: Sec 3.2.3: The first 2 sentences are largely redundant with text above.

AC14: We agree, and this has been changed.

RC15: Fig 3: I may have said this before: the large Mediterranean source may be bogus. This is a problem in our estimates using QIBT also, which we were never able to eliminate - a general problem of after-the-fact approaches including WAM-2layers to estimating sources from reanalyses data at low time resolution (much lower than model time steps). The low-level convergence of moisture over the Sahel in the rainy season is between moist air coming from the south and very dry air from the north. The two sides get convolved and impossible to sort out from reanalysis wind fields when tracing backwards in time. Atmospheric models that include water vapor tracers do not show such large moisture transports from the Mediterranean across the Sahara.

AC15: Thank you for the comment, and we appreciate the nuanced comparison between our two approaches to moisture tracking. Based on your suggestion, we have adjusted the boundaries of our figure, and added some comments about this potentially spurious finding (see below). We did not want to arbitrarily remove this section from the actual analysis, but re-framing the plotted domain in Fig 3, so that the Mediterranean sources do not appear may help avoid any confusion.

We hope these changes are sufficient in your view.

“Our method detected some contribution from the Mediterranean Sea, but this is likely spurious, and due to the inability of moisture tracking models such as the WAM-2layers (as well as other *a posteriori* tracking models) to disentangle the origin of moisture convergence in this region, specifically the mixing of dry air from the north with moist air from the south.”

RC16: P16 L7 (or actually in the reference): GRAIN is an acronym for "Genetic Resources Action INternational" that needs to be expanded.

AC16: Thanks you for this comment. We have actually found an alternative reference, since there are open-access sources on this particular topic, which may be more reliable than sources from advocacy organizations.

<http://www.landmatrix.org/en/about/#how-should-i-cite-the-land-matrix-global-observatory>

RC17: P16 L27: "influence" implies intent; better to say "affect".

AC17: Thank you for this comment, this has been changed.

RC18: P17 L7-8: change "to a low concentration of moisture supply covering Brazil's entire domain" to "to the remainder of Brazil supplying a low concentration of moisture from a large area"

AC18: Thank you for the suggestion, this has been changed.

RC19: P17 L14: "72%" must be a typo. Maybe that's 7.2%?

AC19: Indeed, this should be 7.2%, this has been changed. Thank you for catching such a glaring mistake.

RC20: P17 L30: Change "led" back to "lead" - needs to be present tense.

AC20: Thank you, we agree; this has been changed.

RC21: P19 L12: "Rondônia should have a circumflex over the second o.

AC21: Thank you, we have added the circumflex.

RC22: P21 L29: Change "on precipitation" to "of precipitation".

AC22: Agreed, this has been changed.

RC23: P22 L6: Change "contribution" to "contributions".

AC23: Agreed, this has been changed.

RC24: P22 L11: Add "For instance," before "Nigeria experiences..."

AC24: Thank you, this has been changed.

RC25: Sec 3.4.3: Note somewhere that this subsection refers to the green lines in Fig 5.

AC25: Great suggestion, we have added this to the paragraph.

RC26: P26 L24: I suggest changing "ability" to "potential" or "possibility" - as this is not a solidly proven result. To my knowledge, no one has done water isotope analysis, for instance, to establish the veracity of this model result.

AC26: Fair point, we have changed the language to more accurately reflect the statement.

RC27: Bottom P 27: Change "export of moisture" to "export of atmospheric moisture" so it is clear you are not referring to transboundary rivers.

AC27: Thank you, this has been changed.

REFEREE #5 (ANONYMOUS)

Review of 'On the social dynamics of moisture recycling' by Patrick W. Keys and Lan WangErlandsson

RC1: The article presents a new framework for understanding social ecological processes in regions sensitive to moisture recycling processes. The framework is novel and interesting. I applaud the authors for moving outside their comfort zone to give new insights on this issue. In general, however, I think the framework presented has limitations that I would like to see the authors critically reflect upon and explicitly mention in the text.

AC1: Thank you for the detailed and thoughtful comments.

General Comments

RC2: Two-way social feedbacks are only relevant in a minority of cases. Biophysically it is clear that there is a one-way relation between source and sink regions regarding moisture recycling. I.e. changes in the source region can impact moisture recycling which can affect rainfall in the sink region. The authors state that social processes give rise to two-way feedbacks between the source and the sink. This is true but only in cases where there is tight coupling of trade in agricultural commodities between the source and sink region. For example, change in land use in the source region may reduce rainfall in the sink region. This reduces yields and increases market demand for agricultural crops. This demand can essentially be transmitted anywhere. There is only a positive socio-environmental feedback between the source and the sink if increased demand in the sink region (caused by reduced rainfall and reduced yield arising from land change in the source) is met by exports from the source region. I.e. increased demand in the sink may stimulate more land use change in the source which may reduce moisture recycling further. Other than this specific case, I cannot see a mechanism for socio-environmental feedbacks between the source and sink region. Please correct me if I am wrong on this.

AC2: Thank you for this thoughtful comment. The primary way that we include trade in our discussion is via the key import and export partners discussion, the brief section on land acquisitions, and the inclusion of 'markets' in Figure 5 or the Archetypes discussion. We do certainly agree that trade is a critical aspect of sink-to-source connection, but we think there are several other kinds of connections. First, political power could be a connection, where a sink region has more political power than a source region and can thus mandate that certain land-use actions take place. Second, international law could be used (hypothetically) if a sink region can prove it experienced harm as a result of actions taken by a source region. Third, informal or nonbinding agreements could serve as a platform for sink and source regions to discuss land-use outside of regulatory action or political mandate. These are just a few of the examples that we discuss in the paper, but we think they are indicative of a much broader set of social connections than trade alone.

RC3: Thus, to understand the relation between social changes and moisture recycling, you should focus on where the demand that drives land use change in the source region comes from. In most cases it is probably very local (subsistence), within a country or regional and international that you mention.

AC3: We agree that trade can be a useful, but we do not think it ought to be the only focus for identifying relevant land-use changes.

RC4: You discuss these archetypes, but it is not obvious to the reader that they reveal that that two-way social feedbacks between source and sink are of relatively minor significance when you go to the regional or tele-coupled archetype. It seems that you are trying to fit an SES framework between source and sink regions with regard moisture recycling, when it will only be relevant in a minority of cases. SES within source and sink regions is no-doubt important, however.

AC4: Thank you for the comment. The SES framework as we use it simply a basis for thinking about human-environment interactions as a coupled system. We intentionally steer clear of more in-depth SES theory since we believe that is outside the scope of this particular work. We consider the SES framework to remain relevant at larger scales, in part because as the system expands, the source and sink regions will remain SES regardless of the regional and tele-coupled dynamics. The social connections, we argue, are what make the SES expand spatially, beyond the local scale. We will, however, reflect on this discussion for future work.

Comparison with river systems

RC5: In general, the biophysical characteristics of a moisture recycling system are similar to that of a river system. I.e. upstream users impact downstream users via biophysical changes but not the other way around. However, social changes may be in both directions. A river system differs from the moisture recycling case as the leverage points, as you term them, are specific (such as governance of a reservoir), whereas in a moisture recycling scenario they are highly diffuse and heterogeneous. I.e. Large area of variable landscape types and agricultural practices. Equally, the social and economic links are similar but perhaps stronger in river system, owing to the organisation of societies and trade around rivers. Also, users clearly understand where source and sink regions are in a river system, whereas this is not widely known in moisture recycling systems, and thus issues such as fairness of resource sharing are not widely recognised. There has been much work done examining upstream and downstream social and biophysical feedbacks in river systems which would provide a good template for this work, rather than trying to reinvent the wheel. I would like to see a more complete review of this literature (I only see the reference of Grumbine et al., 2012) and explanation of the similarities and differences between a river system and a moisture recycling system.

AC5: Thank you for this very insightful comment. We agree that there is a great deal to discuss regarding the many possible similarities and dissimilarities between moisture recycling systems and river systems. However, the amount of material that is required for this comparison and discussion is far too much to include in the current manuscript. We aimed for this manuscript to be an introduction of this idea of social connections within moisture recycling systems, and that hopefully it can serve as a springboard for other research to discuss, critique, or even include as a basis for future MRSES study. If we do not have an opportunity to tackle this important comparison between precipitationsheds and watersheds, we hope that someone else does.

Specific Comments

RC6: Page 1 Line 18-19 “socio-meteorology and socio-climatology” These concepts are surely central to the IPCC working group 2 and 3 reports.

AC: These are emerging disciplines with some nascent discourse related to weather, climate, and deeper integration of society and sociology within the research itself. There are a handful of references to either concept, but only ever in passing. Though there is of course a vast field of meteorological and climate impacts research, we do not think that is the same as a true blending of social science methods with meteorology or climatology. It is certainly true that not everything needs a new discipline or a new name, so it will be interesting to see to what extent these emerging notions of socio-meteorology and socio-climatology gain traction, or wither away.

RC7: Page 2 Line 12: Why should it have a social focus? What if natural scientists are examining the biophysical processes? Perhaps you mean “social component”

AC7: Thank you for the suggestion, we will make the change to component.

RC8: Page 3 line 1-10 Are you using an SES Framework? If so, outline specifically the framework you use, rather than SES type of thinking.

AC8: Thank you for the suggestion. Since we are using SES type of thinking we consider our treatment of the field sufficient for this work. We are drawing attention to the theoretical lineage of Holling, Gunderson, and Folke with our citations (later on Page 3), which for our purposes is illustrative of how we are using the concept. As we said previously, we are not delving into the theory of different SES approaches, and rather using the SES approach more broadly.

RC9: Page 3 line 11-12 “Hydrologists specifically”, however moisture recycling is more in the subdiscipline of meteorology that focuses on land-atmosphere feedbacks.

AC9: This is a very good point. We will change the sentence to say: “will provide Earth system scientists who study the atmospheric water cycle”

RC10: Page 5 Tele-connection definition. I have never heard of a teleconnection referring to connection separated by time alone. In climatology I am only familiar with connections separated by space or space and time combined.

AC10: This is an excellent point, we have changed this to “separated by space or space and time.”

RC11: Page 7 line 16 km is in a different typeface.

AC11: Thank you for catching this, we have fixed this.

RC12: Defensive language used which doesn't come across well: e.g. Page 7 line 30-34, Page 8 line 4-5, Page 23 Line 22 – 34

AC12: We agree this is coming off as defensive (and in some cases offensive) and will adjust the phrasing accordingly. Part of this work was to jounce the reader a bit out of the normal scientific delivery of material, but still, this is too much. Thank you for highlighting this.

RC13: Page 8-19 In the results you cover many aspects of the economy within and between countries and many traded commodities. In one way every aspect of an economy is inter-related either directly or indirectly. However, the complexity of economies is such, that it seems necessary to narrow down analysis to the most relevant variables. Therefore, it would be helpful to constrain analyses to the agricultural economy. For example, France, Thailand, Malaysia and

China are Niger's major trading partner (in terms of value) but not in agricultural products, thus what is the relevance here? You can find agricultural trade data from the FAOstat website.

AC13: Thank you for this comment. While we agree that agriculture is very important, it is not the only land-use change that matters. For example, large-scale changes in forest cover or extensive mining can have significant impacts to evaporation. We certainly agree that considering a full economy is too complex. However, our purpose for considering who the trading partners were was to identify whether trading partners overlapped with key moisture source regions. For example, in the case of Niger, its trading partners did not overlap very much with the precipitation shed, so the economy was not considered a very important social connection.

RC14: Page 17 Line 13 – 25 It seems that these two paragraphs are only relevant to a source region. You should state here whether you refer to source, sink or the link between the two.

AC14: Thank you. When reading this section with your comment in mind, we now see that it can be confusing. We will add a sentence clarifying our meaning.

RC15: Page 18 Fig 5. I find this figure too complex. I would prefer an individual diagram for each archetype. Also, it is unclear what the arrows mean. Are they biophysical fluxes or social influence or resource flows? Some indication of the difference between material and immaterial links would be helpful as you have done in figure 1.

AC15: Thank you for your comment. Earlier referee comments suggested that the figure would be better as a single figure, which we agree with, since it is possible to see the whole structure at once. We explored how to add more information to the figure, e.g. physical water flows vs. 'policy flows', but the figure rapidly became too cluttered. Your suggestion does highlight a need for a better statement of our explicit exclusion of this information for visual simplicity. We will add text explaining this.

RC16: Page 20 Line 1. What feedbacks?

AC16: Thank you. We have added an example of the type of feedbacks we implied.

RC17: Page 21 Line 27: You talk about feedbacks but how do these actually emerge in your system? Feedbacks emerge from mechanisms that reinforce an initial change in the direction of that change. I guess here you are discussing positive socio-environmental feedbacks. So, what changes in the social or environmental realm (in source, sink or between the two) and how is that reinforced (in source, sink or between the two).

AC17: Thank you for the comment, and we have added an example of this to the text, per the Referee's previous comment.

RC18: Page 23 line 10 pitfalls of their

AC18: Thank you, this text was changed in response to RC20 below.

RC19: Page 23 line 14 is a prerequisite

AC19: We agree.

RC20: Page 23 Line 7-20 Lecturing of natural scientists seems to me slightly ungrounded. What is your evidence that nearly all natural scientists assume that every meaningful assertion ought to

be verifiable or provable logically or mathematically? This is certainly the case when dealing with natural systems but in my experience there is openness of those engaging in interdisciplinary science to alternative worldviews. Either way, we natural scientists, and sound social scientists, certainly like evidence, however you provide none for these assumptions. Perhaps, perceptions of natural and social scientists on interdisciplinary science could be a study by itself grounded upon sound social science approaches such as surveys, co-publication network analysis etc. Thus, I would leave this part out of your paper or at least dampen the tone a great deal.

AC20: Thank you for the thoughtful comment. We agree that the phrasing is too strong. We will dampen the tone.

RC21: Page 23 line 33 well with research

AC21: Thank you for catching this. We have changed it.