Dear Dr. Kleidon:

Please find attached a revision of the manuscript entitled "Recent changes of relative humidity: regional connection with land and ocean processes" to be considered for publication in Earth System Dynamics. In the revised manuscript, we have addressed all comments and suggestions raised by you and the third reviewer. You will also find enclosed a letter that includes a detailed point to point response to all comments.

We look forward to hearing from you at your earliest convenience, and should you have any questions please feel free to contact us.

Sincerely,

Sergio M. Vicente-Serrano and coauthors

Editor Comments:

Your manuscript was re-reviewed by a third reviewer. This reviewer raised some concerns similar to one of the reviewers of the first round, namely that the causality of your results in some parts of the manuscript are not sufficiently attested and discussed. This reviewer recommended rejection as the reviewer considered the current version far from being acceptable for publication, but encouraged to resubmit after these issues are addressed. The concern of the reviewer particularly refers to section 3.3. I agree with the reviewers assessment that this section takes an approach that is too simple to interpret RH changes in terms of evaporation changes. Correlation does not imply causation, especially when dealing with the hydrologic cycle with its very tight linkages between evaporation, humidity, and precipitation. Also note that the aerodynamic term in evaporation is typically quite small, and evaporation is predominantly limited by energy. So it is unclear to me what the correlation between RH and evaporation is supposed to imply.

We understand the concerns raised by the reviewer. We agree with the reviewer that in the earlier version we lacked the opportunity to provide a detailed and comprehensive interpretation and discussion of the obtained results. Moreover, in our attempt to attribute the possible physical mechanisms driving the observed RH, we probably biased the interpretation of the results toward a higher importance of land evapotranspiration processes, given the obtained empirical relationships. In the revised manuscript, we have carefully considered this by making a re-elaboration of the interpretation of the obtained results, and entirely rewriting the discussion and conclusion sections.

In the revised manuscript, we agree that RH correlation with several physical mechanisms does not imply true causality. Within the text, we have not established this direct possible causation related to the evapotranspiration variability and trends. Correspondingly, we also stress the cases in which a coherent and reasonable connection between RH and land evapotranspiration can be attributed given not only on the correlation among the two variables but also the coherence of the detected trends and the contribution of continental and oceanic sources to moisture supply in specific regions. This is widely discussed below in our response we provide to the reviewer.

In relation to the comments related to the aerodynamic and radiative connections, we agree that the radiative component can be important in explaining the magnitude of the Atmospheric Evaporative Demand (AED). Here, I would like to establish a distinction between the AED, which is exclusively driven by the atmospheric variables that control the aerodynamic (air temperature, Relative humidity and wind speed) and radiative (downward direct and diffuse radiation) components and the real (or actual) evapotranspiration (ET) (better than evaporation, since transpiration is much more important than direct evaporation), which does not only depend on the AED but also on the soil water availability. In arid and semiarid regions, land evapotranspiration is mostly driven by soil water availability and thus the AED exceeds very much ET. In humid climates, where there are no water constrains, ET is mostly constrained by the AED.

There is evidence that the role of the radiative component on the average magnitude of the AED (here different forms of AED could be valid for this statement, e.g. Pan evaporation, reference evaporation, ETo) may be strongly variable at the global scale and in some regions the aerodynamic component is even more important in explaining the magnitude of the AED than the radiative component. In any case, and irrespective of the relative importance of both components on the AED magnitude, the existing evidences on this issue not only at the global scale, but also in regional studies, suggest that the aerodynamic component explains most of the observed temporal variability of the AED. Thus, it is important not only to consider the sensitivity of the AED to the different meteorological variables, but also the observed trends of the variables that control the AED. Observations suggest that meteorological variables that control the aerodynamic component show-on average- more changes than the incoming solar radiation (e.g. McVicar et al., 2012a; J. Hydrol., and 2012b J.; Ecohydrology) and the aerodynamic component is the main explanatory factor of the recorded AED trends at the global scale (Wang et al., 2012, J. Clim., 25, 8353–8361). We also analysed this issue in depth in Spain (Vicente-Serrano et al., 2014 Water Resources Research 50, 8458–8480) using observational 50-yrs data, concluding that AED is more sensitive to temperature and relative humidity than to solar radiation. We found that the strong AED trends recorded over the last 50 years are mostly driven by the strong decrease in RH. A similar pattern is found also in the Canary Islands (Vicente-Serrano et al., 2016, Hyd. Earth Sys. Sci. 20, 3393-3410). Other studies have stressed the role of wind speed in particular regions (e.g. Gu et al., 2018: Atmosphere 9: 9; Wang et al. 2017: J.Hydrol 544: 97).

Nevertheless, and irrespective of the comments raised in this revision on the importance of the meteorological drivers of the AED, we have not analyzed the possible role of aerodynamic and radiative components on land evapotranspiration, as well as the possible influence of land evapotranspiration, oceanic evaporation and moisture transport issues on the temporal variability and trends of RH. Although this issue is of particular relevance, given the strong influence of RH on the AED, this issue is out of the scope of this research, particularly with the uncertainty in attributing RH to different physical processes. Alternatively, in this first-time comprehensive empirical retrospective analysis, we have stressed the ways in which both oceanic and land mechanisms can probably contribute to explaining the spatially complex RH trends found in this study. We agree with the reviewer that oceanic contribution is essential in large regions of the world and some mechanisms related to the different warming between land and oceanic areas could contribute to better explanation and understanding of the decrease of RH in some regions. Nevertheless, land contribution is also important in explaining RH and AED anomalies in some regions. This has been stressed in a number of studies, as we have indicated in the discussion section, as follows:

"…In the same context, there is strong evidence that low levels of soil moisture and land evapotranspiration are usually accompanied by a reinforcement of low RH, particularly during drought episodes. Under these circumstances, the suppression of the latent heat flows from the soil to the atmosphere would enhance soil and vegetation warming and sensible heat, inducing air temperature rise. Also, the lack of supply of water vapor to the atmosphere favors the decrease of RH and the reinforcement of severity of heat waves (Hirschi et al., 2011). Seneviratne et al. (2002) showed that vegetation control on transpiration might contribute significantly to enhancement of summer drying, particularly when soil water is limited. Other studies confirmed this finding for other regions worldwide, employing both observational data (e.g. Hisrchi et al., 2011) and model outputs (e.g. Seneviratne et al., 2006; Fischer et al., 2007). Our study suggests good spatial agreement between changes in RH and those of continental contribution to precipitation as well as land evapotranspiration during summertime. Although this finding is markedly evident for all the analyzed regions, it should be seen with caution. This is mainly because physical processes driven soil moisture are more active during the warm season (Vautard et al., 2007 and 2013; Miralles et al., 2014), which adds difficulty to establish full causality between RH and other driving forces during this season."

This is a relevant and desired research topic to analyze in depth (see e.g. a recent granted ERC project that focusses on the role of land evapotranspiration on AED and how these issues may cause aggravation and/or spatial propagation of droughts given the decrease in air moisture and land supply anomalies; http://www.dry2dry.org/context).

Furthermore, at the moment, Section 5 merely summarizes the findings, but they are not conclusions. I think there is more to say from your results, so more work should be done on formulating what the analysis actually implies regarding the causes for RH trends.

We have rewritten the conclusions section of the manuscript, including an assessment of the findings related to the possible drivers of the observed RH trends:

"This study analysed relative humidity (RH) trends at the global scales using observations and ERA-40 data. It extended further to link RH trends with a range of variables, which can give indications on the possible oceanic and continental contribution to RH trends. As opposed to the widely-accepted constant RH scenario under global warming, our results suggest significant RH trends over many regions worldwide, but including: There are positive trends in RH over specific regions (e.g. high latitudes of the North Hemisphere, Northern South America, India, West Sahel), which is in contrast to the generally dominant negative trend at the global scale. This decrease is mostly linked to the temporal evolution of RH during the boreal warm season.

There is a strong diversity in the observed RH trends, highlighting the complex and divergent role of different physical processes and drivers, including dynamic and thermodynamic processes. In general the supply of specific humidity is a main source of the observed RH trends since there is a high agreement between RH and specific humidity trends at the global scale, suggesting that moisture deficit contributes to RH variability, in opposition to atmospheric warming. This finding suggests that the evolution of specific humidity in vast areas of the world has not provided the necessary humidity to maintain RH constant according to the observed warming trends. This feature is important, given its implications in terms of atmospheric evaporative demand and aridity conditions under the current climate change scenario.

This study also analyzed the possible contribution of continental and oceanic moisture supply to explaining the magnitude and spatial patterns of RH trends. For this purpose, fourteen regions were defined and the contribution of continental and oceanic sources to RH in these regions was assessed using a Lagrangian scheme. Results indicate that no single physical mechanism can be responsible for the observed trends in RH at the global scale. Globally, there are two well-recognized hypotheses for explaining the possible decrease in RH under a global warming scenario: (i) the land water supply by means evapotranspiration processes, and (ii) the insufficient oceanic moisture supply to maintain continental RH constant under different warming rates between continental and oceanic regions. Our findings stress that these two hypotheses could act together to explain recent RH trends. However, although it is quite difficult to establish a direct causality between RH and different underlying processes and driven variables using different empirical sources, the observed decrease in RH in some regions (e.g. La Plata) can be linked to the lower water supply from land evapotranspiration. In other regions, the empirical relationships suggest dynamic and thermodynamic mechanisms related to moisture supply from oceanic source regions (e.g. Amazonia and Western North America). Taken together, these physical mechanisms could coexist in some analyzed regions, given the strong relationship found between precipitation, RH and land evapotranspiration. This strong coupling among these variables makes it difficult to establish a direct physical attribution of RH variability.

Overall, this study confirms the strong complexity of determining a general physical process that may explain the complex spatial patterns of RH trends, particularly at the global scale. As such, further research is still needed to unravel the complex physical factors driving the dominant RH negative trends over large continental regions. The availability of long-term historical and reanalysis data and the advancement of modelling approaches is an asset in any future research to explore whether the land and oceanic processes drive the observed RH trends

Understanding current RH is relevant in hydroclimatic research, due to its impacts on atmospheric evaporative demand, crop development and yield, forest fire risk, bioclimatic comfort, besides other hydrological processes. This study provides the first comprehensive analysis of RH at the global scale based on empirical information, comprising state-of-the art modelling approaches and forcing scenarios."

Comments by reviewer 3:

This study investigated the change of RH and its relationship with land and ocean hydrological variables. My major comment is the same as that by an earlier reviewer (H. F. Goessling): "Here and generally, I have the impression that the suggested causality is not sufficiently attested and discussed. I would argue that increased land ET tends to be caused primarily by increased precipitation (except in very humid regions), and that anomalous precipitation (caused, e.g., by circulation anomalies) is simply accompanied by corresponding RH anomalies. I suggest this could be the main explanation for the positive correlations between RH, precipitation, and land ET."

About the contribution of nonlocal moisture sources, the strong correlation also does not suggest causality, because all the variables in the hydrological cycle could be controlled by atmospheric circulation, leading to strong correlation. Please refer to the following paper, and it can provide you some clue on the relationships among RH, SST and ocean ET.

Wei, J., Q. Jin, Z.-L. Yang, P. A. Dirmeyer, 2016: Role of ocean evaporation in California droughts and floods, Geophysical Research Letters, 43, 6554–6562, doi: 10.1002/2016GL069386.

In summary, although the study investigated an important and interesting topic, it did not produce any major finding that is new and useful and did not give any solid conclusion on the causal relationships. Therefore, the paper is still far from acceptable for publication.

Here, our intention was not to provide a causality of the temporal variability and trends in RH at the global scale. Alternatively, we have stressed the strong complexity of this issue. As opposed to earlier studies that have employed modelling approaches with GCM scenarios to determine the possible connection between RH trends and different physical mechanism related to moisture transport from oceanic areas, the differences between the warming of oceanic and continental areas (since they affect air saturation), but also the role of land evaporation processes. In this study, we have employed empirical information, reanalysis data and statistical tools to establish possible relationships that may give insights on the possible drivers of RH temporal variability and trends.

A detailed response to this point is outlined in our response to Dr. H.F. Goessling, which was included in the revised manuscript. As we completely agree that correlation does not necessarily imply causality, we have been careful with the issue of "causality", This aspect has been stressed several times in the revised manuscript:

"In any case, ***attributing causality to the observed RH changes is quite complex given divergences found at the global scale****. We have computed the fraction of continentally-originated humidity for each region and season and related this fraction to the strength*

of the agreement between RH and Land evapotranspiration at the annual and seasonal scales. Supplementary Table 1 shows the percentage of contribution of continental areas to the total moisture in each one of the fourteen analyzed regions, which oscillate between 31.6% for West Europe and 64% in Northeast Asia. There is not a significant relationship between these percentages of contribution and the strength of the agreement between RH and land evapotranspiration obtained in each region (Supplementary Figure 47). ***<u>This reinforces the complexity of attributing changes of RH to a single factor.</u>*** *In any case, in some of the regions that show significant changes in RH have been identified, there are also changes in the total contribution from continental areas at the seasonal and annual scales (Supplementary Figures 48-50). Both West Sahel and East Sahel show increased contribution of continental areas. On the contrary, La Plata region, in which there is also a strong agreement between RH and land evapotranspiration and that shows a significant negative trend in both variables, there is a decrease of the continental contribution.* ***<u>This stresses the complexity of giving a unique attribution to the observed RH changes.</u>****"*

We completely agree with the reviewer that moisture supply from oceanic regions can contribute significantly to explaining precipitation (and RH) variability over large continental regions. As such, the discussion section was entirely rewritten to clarify this kind of issues and avoid any misinterpretation of what can be really inferred with the statistical analysis of different empirical information applied here.

Nevertheless, we would like also to stress that the scope of our study was not to explain the general contribution of continental and/or oceanic sources to RH. Instead, we try to understand the mechanisms that drive the occurrence of different trends in RH at the global scale, in connection to trends in land evapotranspiration, oceanic evaporation, and (now in the revised manuscript) with the moisture supply from oceanic and continental sources.

In the same context, we would like also to stress that anomalies in land evapotranspiration, accompanied with low soil moisture, may cause changes in RH, given the balance between latent and sensible fluxes. We have stressed this point in the revised manuscript, with no direct causality using our empirical information:

"…In the same context, there is strong evidence that low levels of soil moisture and land evapotranspiration are usually accompanied by a reinforcement of low RH, particularly during drought episodes. Under these circumstances, the suppression of the latent heat flows from the soil to the atmosphere would enhance soil and vegetation warming and sensible heat, inducing air temperature rise. Also, the lack of supply of water vapor to the atmosphere favors the decrease of RH and the reinforcement of severity of heat waves (Hirschi et al., 2011). Seneviratne et al. (2002) showed that vegetation control on transpiration might contribute significantly to enhancement of summer drying, particularly when soil water is limited. Other studies confirmed this finding for other regions worldwide, employing both observational data (e.g. Hisrchi et al., 2011) and model outputs (e.g. Seneviratne et al., 2006; Fischer et al., 2007). Our

study suggests good spatial agreement between changes in RH and those of continental contribution to precipitation as well as land evapotranspiration during summertime. Although this finding is markedly evident for all the analyzed regions, it should be seen with caution. This is mainly because physical processes driven soil moisture are more active during the warm season (Vautard et al., 2007 and 2013; Miralles et al., 2014), which adds difficulty to establish full causality between RH and other driving forces during this season."

We agree with the reviewer that atmospheric circulation is an essential factor for better understanding of climate variability, so dynamic processes must be taken into account to provide an overall picture of the variability and trends of RH at the global scale. Thus, we clearly stressed this issue in the discussion section of the revised manuscript, as follows:

"Sherwood (1996) indicated that RH distributions are strongly controlled by dynamical fields rather than local air temperatures. This suggests that atmospheric circulation processes could largely affect the temporal variability and trends of RH. A range of studies indicates noticeable changes in RH, in response to low-frequency atmospheric oscillations, such as the Atlantic Multidecadal Oscillation (AMO) and El Niño-Southern Oscillation (e.g. McCarthy and Toumi, 2004; Zhang et al., 2013), regional circulation (Wei et al., 2016a and 2016b), as well as changes in the Hadley Cell (HC) (Hu and Fu, 2007). Wright et al. (2010) employed a global climate model under double CO2 concentrations to show that tropical and subtropical RH is largely dependent on a poleward expansion of the Hadley cell: a deepening of the height of convective detrainment, a poleward shift of the extratropical jets, and an increase in the height of the tropopause. Also, Laua and Kim (2015) assessed changes in the HC under CO2 warming from the Coupled Model Intercomparison Project Phase-5 (CMIP5 model projections. They suggest that strengthening of the HC induces atmospheric moisture divergence and reduces tropospheric RH in the tropics and subtropics. This spatial pattern resembles the main areas showing negative trends in RH in Northern as well as Southern hemisphere."

We have revised the discussion section, following the comments raised by the reviewer and relevant discussion in other related articles. Again, our objective was not to connect variability and changes of RH with atmospheric circulation processes, but to relate with temporal variability and trend of some climate/hydrological/oceanic variables that can drive the temporal variability and the trends of RH. As we stressed above, we have not tried to establish causality, but rather to stress the complexity of the mechanisms and to explore statistically significant relation that may provide some clues on the factors affecting RH variability and trends worldwide. We believe that modelling approaches are valuables tools to unravel the complex physical mechanisms behind RH variability and trends. Studies based on empirical information are also essential to evaluate the confidence of the suggested processes and the statistical robustness of the expected coherent relationships.

Some specific comments:

1. Instead of land ET and ocean ET, can you calculated the relationship of RH with the land and ocean moisture contribution to precipitation (E-P)? I guess the RH relationship with ocean moisture contribution should be stronger than with ocean ET.

In the revised manuscript, we analyzed the relationships between RH and land and oceanic moisture contribution to precipitation (E-P). In the revised manuscript, we have included a new section (3.2), in which we explain in depth these relationships.

2. L78. add "increases" after "specific humidity"

Added

3. L247. I think 95th percentile of E-P is not a good criterion because there are very large areas have very small E-P values. It is better to use 95% moisture supply criterion, i.e., the selected area contributes 95% of the moisture for the target region's precipitation.

We have selected the 95th percentile to limit the higher extension area for the sources of moisture, to account for the main sources, and to plot a continuous line in the figures. In previous works, we have adopted the same threshold or high (98th percentile) to achieve a better and realistic contribution of moisture. In any way, the percentile selected is near the 95% of the values, due the fact that the field has a continuous pattern in its extension, without jumps that could affect the calculation of percentage or/and percentiles.

4. Page 12. From line 290. The discussion for supplementary Figure 1 is very long. If it worth such long discussion, it should be a formal figure, not a supplementary figure.

Supplementary Figure 1 has been included in the main manuscript, as Figure 1.

5. L290-291. Vertically Integrated Moisture Flux (VIMF). How is it calculated? Is it E-P from FLEXPART? I feel it is not the normal VIMF (qv) people talking about because in Line 300 you mentioned "Evaporation is higher than precipitation over …"

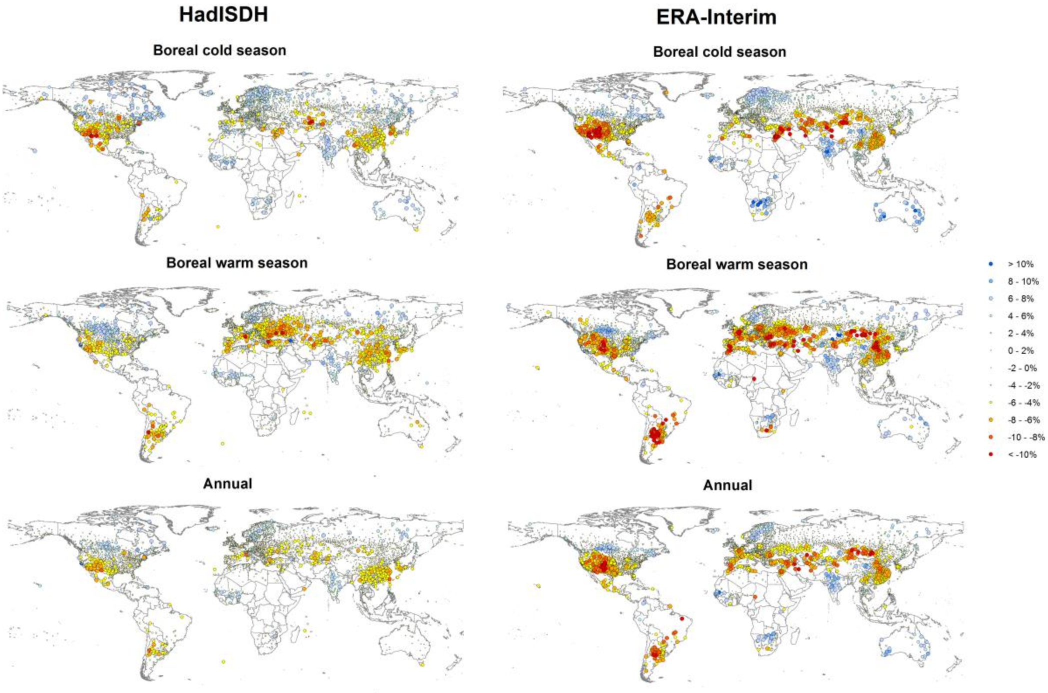
VIMF is calculated directly from the ERA-Interim reanalysis data. Evaporation and precipitation in this interpretation are related with divergence and convergence field in the VIMF plot.

6. L296 "regions" should be "seasons"?

Replaced

7. Figure 2. You should add some figures that shows only the ERA-Interim data with the same available grids as the HadISDH. In this way, the comparison is more accurate.

We have included the suggested figure, as Supplementary Figure 1.



Supplementary Figure 1: Spatial distribution of the magnitude of change of RH (% per decade) over the period 1979-2014 from HadISDH (left) and ERA-Interim dataset (right) considering the points with available HadISDH observatories

8. L730. "not" should be "no"

Replaced.