Response to referees' comments (hess-2019-281)

We would like to thank the reviewers for their professional, detailed and constructive comments, which improved our manuscript considerably. We have carefully revised the manuscript following their comments point by point. Our revisions and explanations have been inserted in blue, and all amendments are also highlighted in the version of revised manuscript. Additionally, the writing of our revised manuscript are also under carefully editing by English native speaker with specialized in hydrology.

Anonymous Referee #1

The manuscript "Widespread decline in terrestrial water storage and its link to teleconnections across Asia and Eastern Europe" by Liu et al., submitted to HESS, analyses the terrestrial water storage (tws) for regions with declining tws based primarily on GRACE, hydrological modelling data and literature values, links it to a huge number of teleconnections and separate tws both in seasonality and compartments and link it as well to teleconnections. While the manuscript started promising (and the idea of linking TWS dynamics to teleconnections is interesting), it has several drawbacks both structural and content-wise. Simultaneously, I have the impression that the manuscript was not prepared carefully and properly reviewed by the co-authors before the submission. Otherwise I could not understand the number of the major and minor very obvious problems that made it hard to focus on the content of the manuscript. In sum, I have doubts, if a major revision could lead to an acceptable improvement for the high journal standard and therefore recommend to reject the manuscript but I of course leave it up to the editor if the chance for improvement should be given.

Response: Thank you for your comment. We feel sorry for the confusion and inconvenience we have brought to you. In the revised manuscript, we have substantially revised our manuscript according to the reviewers' comments.

Major comment

(1) The general objective of the paper is interesting (especial the link to teleconnections) but how the authors structured the manuscript is not convincing.

Response: Thank you for your comment. We have reorganized the data and method, result and discussion section according to referee's comments, particularly in the result interpretation and discussion content.

(2) The method section does not provide the details that are needed to understand the results. Should the reader know every single teleconnection? What are the methodological details of assessing water storage changes for lakes (e.g. are reservoirs included?), how are glaciers included (a reference to literature does not allow a reader to really get a clue how specifically the data has been included in this study)? Wetland and river storage seem to be missing at all in the study – at least those are not indicated in the definition or in data sets used.

Response: Thank you for your comments. In our revised manuscript, we have tabulated the datasets used in our study. The lakes and glaciers that considered in our study are listed in the table (Table 1). The rivers and reservoirs indeed not included in our study, we have discussed the associated uncertainties in discussion section. We also made a methodology flow diagram of data processing in our revised manuscript (Figure 2, marked by the figure number in the revised manuscript, hereafter).

Table 1: Descriptions of datasets used in this study

Datasets	Variables	Time span	Resolution	Source
GRACE	JPL-M	2002-2017	monthly and 0.5°	The Jet Propulsion Laboratory (Watkins et al., 2015) and the Center for Space Research (Save et al., 2016)
	CSR-M			
GLDAS	Canopy	2002-2017	monthly and 0.25°	The Global Land Data Assimilation System data (Rodell et al., 2004)
	Soil moisture			
	Snow water			
Lakes	Caspian sea	2002-2017	ten days and site	The Database for Hydrological Time Series of Inland Water (Schwatke et al., 2015) and Hydroweb (Crétaux et al., 2011)
	Aral Sea (East)			
	Aral Sea (West)			
	Aral Sea (North)			
Glacier	Tien Shan	2000-2016	year and regional	literature (Brun et al., 2017)
	Hindu Kush			
	Spiti Lahaul			
	East Nepal			
	Bhutan			
	Nyainqentanglha			
Teleconnections	AO, NAO, EA, EAWR, WP, polarEA, PNA, IOD, AMO, PDO, ENSO, SCAND	2002-2017	monthly and global	The Climate Prediction Center of the U.S. National Oceanic and Atmospheric Administration

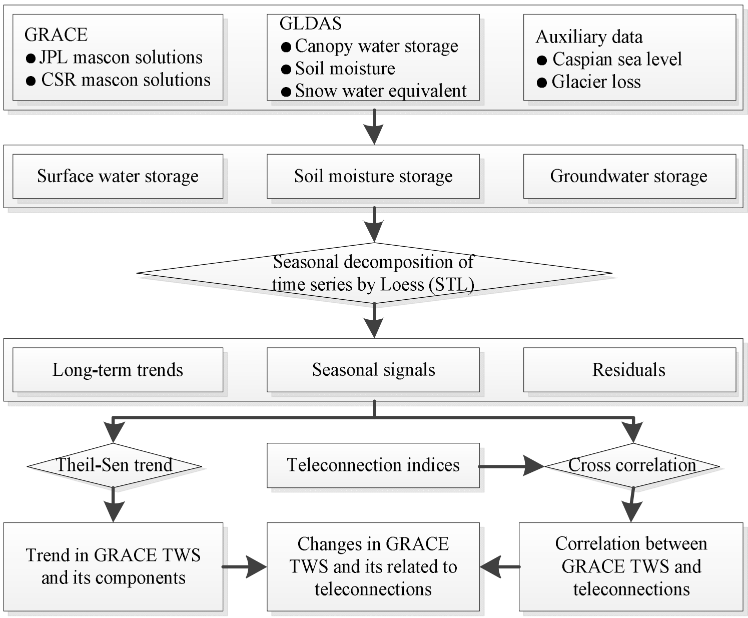

Figure 2: Methodology flow diagram of data processing in this study.

(3) The results section contains a too short and selective description of the results, often followed by an interpretation. Should it be up to the reader what the result of the study or the interpretation is? There are questionable interpretation included, for example that the (very small) changes in precipitation is responsible for the (one magnitude higher) change in TWS, or that glacier melt leads to soil moisture increase – without citing any reference.

Response: Thank you for your comment. We have substantially modified the inappropriate phrasing in results interpretation, and also added citations for each interpretation. Notably, the trend in precipitation was mistake in our former version of manuscript, we have recalculated and reproduced the spatiotemporal changes of precipitation over the study area (Figure 3).

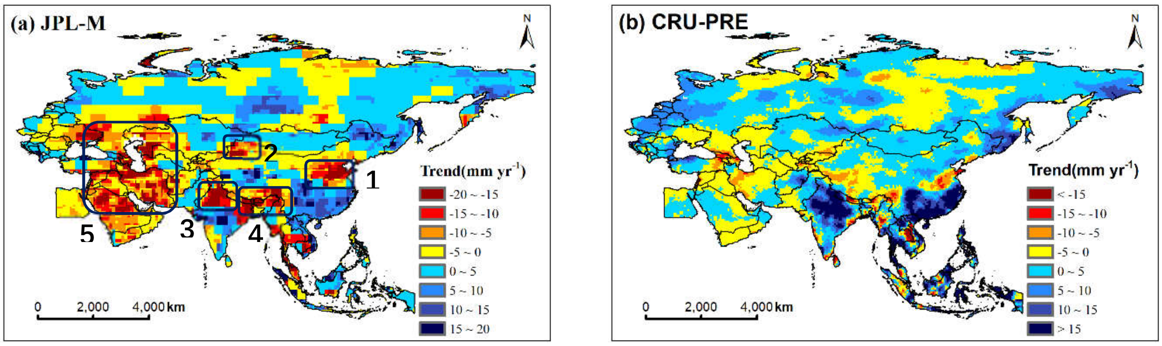

Figure 3: Spatiotemporal changes in TWS as obtained from GRACE (a) and precipitation as obtained from CRU (b) across the Asian and Eastern European regions during 2002-2017. The trend is obtained from the removed seasonal cycle time series.

(4) In the discussion section, the arguments of the results section are partly repeated. The authors are not embedding the findings of their study to the literature (except a very few examples), so it is hard to get a proper information of the robustness of their findings.

Response: Thank you for your comment. We have reorganized the discussion section according to reviewers' comments in our revised manuscript.

(5) Most disappointing I found is that for nearly every figure, major problems arise. Most of the diagrams do not even have a proper axis naming / labelling, so I have hard times to understand the results and the text that is based on it, all that made it hard to review the content.

Response: Thank you for your comment. We feel sorry for the inconvenience we have caused to you. In the revised manuscript, we have reproduced all figures according to the detail comments. We have attached all figures at the end of this response.

(6) More specific, there are (other than mentioned in the state of the art) already a number of global / large scale studies that deal with those or a subset of those regions or even on global scale but often directly include anthropogenic impacts (by the way, those regions could have names), e.g. Wada et al, 2010, Döll et al, 2014,

Scanlon et al, 2018, 2019, Syed et al, 2008, Tangdamrongsub et al., 2018, Zhang et al, 2017 and more, those and some of the references therein should be considered when re-designing the manuscript.

Response: Thank you for your comment. We have carefully read these papers and properly cited them in our revised the manuscript.

Specific comments

(1) For the distinguishing of water storage compartments, a single mascon-solution and a single hydrological model is being used. Few years earlier that would have been state of the art, but now, and especially as a number of GRACE solutions (spherical harmonics and masons) and a large number of hydrological / land surface models are available, this kind of study should be done in a multi-model/multi-data setting to be able to verify the results, provide uncertainty information which then might lead to a valuable scientific contribution. To reduce the approach of the manuscript it to the minimum, the GRACE tws was reduced by NOAH soil moisture, snow and canopy, by lakes and glaciers; the leftovers are then groundwater and/or human interventions. Why have not the authors used a hydrological model (or better more) that consider human interventions, to allow direct assessment of trends / residuals? There are a number of global-scale studies that are using GRACE data in combination with global water models (Scanlon et al., 2018, Döll et al., 2014), especial to trends which contains also a huge list of references within for some of the regions of this study.

Response: Thank you for your constructive comment. The spherical harmonic solutions generally suffer from correlated errors that manifest longitudinal striping in the gravity solution (Rodell et al., 2018). Although largely successful in removing errors, the post-processing also damps and smooths real geophysical signals (Landerer and Swenson, 2012). Recent advances in GRACE data processing have shown that solving for gravity anomalies in terms of mass concentration (mascon) functions with carefully selected regularization results in superior localization of signals on an elliptical Earth (Save et al., 2016). Therefore, two publicly available GRACE mascon solutions are employed in our study: Jet Propulsion Laboratory mascons RL05M (Watkins et al., 2015) (JPL-M) and Center for Space Research mascons RL05M (Save et al., 2016) (CSR-M). Notably, JPL-M has the unique characteristic that each 3° mascon element is relatively uncorrelated with neighboring mascon elements, whereas the 1° mascon elements in CSR-M solutions is highly correlated with their neighbors. Moreover, three degrees correspond approximately to the 'native' resolution of GRACE. Therefore, in this work we mainly used JPL-M for trend analysis and mapping.

(2) Line 72: The Mount Kilimanjaro comes unexpected in this list – isn't it located in Tansania (Africa), or is there also one in Asia?

Response: Thank you for your comment. The Mount Kilimanjaro is indeed located in Africa, we have corrected the mistake in our revised manuscript.

(3) Line 75: The sentence "Under the combined..." needs references or does it belong to the hypotheses?

Response: Thank you for your comment. We have rewritten the study area section and deleted this sentence in our revised manuscript.

(4) Line 79ff: GRACE data, especially in the months at the end of the orbit time shows an increasing error in the signal – have you considered this in your analyses?

Response: Thank you for your comment. There are indeed certain months during which the GRACE orbit is in a near-repeat pattern. This phenomenon leads to sub-optimal spatial sampling and thus typically leads to larger errors in the higher spherical harmonic coefficients. The mascon solutions used in this study have already considered the measurement errors and leakage errors in the final data analyses data product.

(5) Lines 86-94 should be rewritten as it is repeating partly itself

Response: Thank you for your comment. We have rewritten the data section in our revised manuscript.

(6) Line 95: Whereas I agree that two things are comparable in general, please be concise in wording. One can compare an apple with an orange but this is not a good comparison. Comparing full TWS from GRACE with TWS from Noah that consists only of soil, snow and canopy leaves out important compartments such as water bodies, groundwater and glaciers. Of course, this is written in the next sentence but the word "directly comparable" is misleading.

Response: Thank you for your comment. We have rewritten this section and revised the word "directly comparable" in our revised manuscript.

(7) Lines 98 ff: the description of how lake level and glacier change have been used in this study is much to short described. For lake levels – which lakes are included? Only the large ones? Are reservoirs included? Are wetlands included? Which time series are assessed? For example, Wang et al., (2018) ends in 2016, the time series of this manuscript exceeds this.

Response: Thank you for your comment. We have listed the lakes and glaciers used in our study in table 1. But we did not include reservoirs and rivers parts in our study. We have discussed the associated uncertainties in discussion section as follows. Multiple uncertainties remain in understanding the changes in TWS and its components over the Asian and Eastern European regions. These may include the unaccounted for reservoir and rivers in surface water storage, which may induce uncertainties in a certain area in estimating the groundwater by deducting the surface water and soil moisture from TWS. The glacier data used here is during 2000-2016, this inconsistent with our study period (2002-2017) may also cause uncertainties in separating the water components from TWS.

(8) Line 101: If SW does not include wetlands or rivers (at least this information is missing in the manuscript), then the residual of GRACE TWS minus SW and SM cannot be groundwater only.

Response: Thank you for your comment. We indeed not consider rivers and reservoirs parts in our study. We have added the uncertainties in discussion section in our revised manuscript.

(9) Lines 105 ff: The description of the TCs is not very informative. Please provide more details, e.g. for which region they are defined, how they are characterized (e.g. briefly in the supplement).

Response: Thank you for your comment. We have supplemented the briefly introduction of the TCs in data section in our revised supplement.

(10) Lines 113 f: to which TWS does the section refers to? I guess to GRACE TWS, right? The section needs to be reformulated and streamlined for better readability and enriched by references, it reads confused in the current shape. What does the (totaltrend-seasonality) mean? Is it a mathematical equation? Please provide details why by using the cross-correlation of the TWS residuals and TC the interference with (...) are reduced. This is similarly repeated in lines 144 f.

Response: Thank you for your comment. Yes, this section refers to GRACE TWS, we have revised the statement. Also, we have reformulated and streamlined this section according to your useful comment in our revised manuscript.

(11) Line 144: For which GRACE solution the numbers are standing for? The mean of both? Fig 2c shows not “expected” changes in precipitation. And again, such a small precipitation trend in that region as shown in Fig 2b should not affect the tws signal drastically. Similar interpretation problems are following for the next case studies.

Response: Thank you for your comment. Both JPL-M and CSR-M show similar spatiotemporal pattern of changes in TWS (Figure 3 and Figure S3). Since the JPL-M solution has the merit of lack of correlation between neighboring mascon elements in the retrieval, in this work we use JPL-M for trend analysis and mapping. Notably, the trend in precipitation was mistake in our former version of manuscript, we have recalculated and reproduced the spatiotemporal changes of precipitation over the study area.

(12) Line 158: The comparsion of Nort-West-India with one single reference is misplaced in the results section. Due to the reason the authors explain, it is not possible to assess the reason for the difference. I suggest to properly frame the trends into the various estimates that are available from the literature and then, in the discussion section of the paper to discuss it.

Response: Thank you for your comment. We agree with your suggestions, and we have revised the sentences according to the comment in our revised manuscript.

(13) Line 161: What is the assessment of Caspian Sea Level is based on? Is that focus of the paper?

Response: Thank you for your comment. In this paper, we estimated the surface water loss by assessing the decline in water body level of Caspian Sea. The sharply declined in Caspian Sean level could better understand the loss of surface water storage.

(14) Line 163 ff: A mix of (selected) interpretation and presenting results, not easy to follow.

Response: Thank you for your comment. We have redesigned this paragraph in our revised manuscript.

(15) Line 169 ff: It is hard to accept that general conclusion that change in tws correlates with natural variability just because of (the magnitude lower) precipitation trend. This needs to be analysed in much more detail, especially the role of human interventions needs to be considered here (with data/modelling).

Response: Thank you for your comment. The trend in precipitation was mistake in our former version of manuscript, we have recalculated and reproduced the spatiotemporal changes of precipitation over the study area. Challenges remain in separating the long-term relative roles of natural climatic variation and anthropogenic forcing on TWS changes. Well-designed experiments and coupled human-natural system models are still needed to clarify the quantitative contributions of each influencing factor on TWS in our future study.

(16) Line 170 f: A data product that base on the same satellite input but with a different processing is expected to lead to similar results (at least for the broad picture) especially for the highly human impacted regions. This does not allow justification of the results in my eyes. It could provide an uncertainty information, not more. A different measurement system (e.g. GPS displacement analysis) could be a real justification.

Response: Thank you for your comment. We have rephrased this sentence, and rewritten the results section in our revised manuscript.

(17) Lines 182 f (Most regions…): I do not agree to the described pattern.

Response: Thank you for your comment. We have revised this statement in our revised manuscript.

(18) Lines 194 ff: it reads like a new finding that at those locations, groundwater depletion occurs. There is a wide range of previous literature that directly assess regions with groundwater depletion based on GRACE (and hydrological models), e.g. Döll et al., 2014, Wada et al., 2010 and references therein.

Response: Thank you for your comment. We have carefully read these papers and properly cited in our revised manuscript.

(19) Line 199 f: is there any reference that the glacier melt leads to higher soil moisture or is it an interpretation of the results? I am not an expert in glacier hydrology but would assume that the effect of a melting glacier to soil moisture increase is only locally effective and as soon as the glacier water is within a river, soil moisture is affected probably only weak, especially at a larger spatial scales.

Response: Thank you for your comment. In addition to the glacier melt water, the increase in precipitation could also contribute to the increase in soil moisture (Figure 3). We have revised this sentence in our revised manuscript.

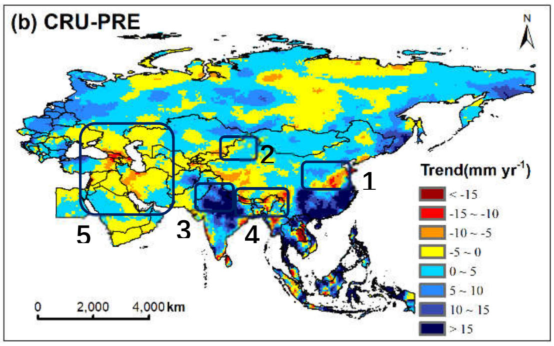

Figure 3: Spatiotemporal changes in TWS as obtained from GRACE (a) and precipitation as obtained from CRU (b) across the Asian and Eastern European regions during 2002-2017. The trend is obtained from the removed seasonal cycle time series.

(20) Line 202: irrigated agriculture contributes to more than a half of tws loss? How has this been assessed? Is assumed that irrigation only stems from groundwater resources? The following lines are already a discussion, it is hard to assess what is the specific contribution of this study.

Response: Thank you for your comment. Actually, groundwater contributes to more than a half of TWS loss in region2 instead of irrigated agriculture. We have rewritten this part in our revised manuscript.

(21) Line 208: the authors refer to a meteorological drought the first time in the manuscript. Is it referring to declining precipitation from Fig 2b? Trends in precipitation does not necessarily imply a drought, this should be clarified.

Response: Thank you for your comment. We indeed inferred drought from declining precipitation, and we have rectified the statement in our revised manuscript.

(22) Line 210: again, everything is comparable. But not everything is similar/equal. Please be concise with wording.

Response: Thank you for your comment. We have replaced the word “comparable” of “similar” in our revised manuscript.

(23) Line 214: which drought definition? TWS is not “recharged”, groundwater can be recharged. What does the word “will” mean? Climate projection? Water use projection? This is not clear.

Response: Thank you for your comment. We have replaced the word “recharged” of “changed”, and we also rephrased this sentence in our revised manuscript.

(24) Line 241: unit?

Response: Thank you for your comment. We have rectified the unit in our revised manuscript.

(25) Section 3.2: I have hard times interpreting and justifying the results. First, maximum correlations are relatively low (Fig. S5) and I guess, only the TC with the dominant correlation is displayed in Fig 2. However, how to interpret plausible, if a correlation coefficient is, let’s assume 0.20 and the next TC has 0.19? The interpretation (such as time lag discussion) solely considers the maximum correlation even though it is in a large part of the study area

very low. A correlation coefficient of 0.2 implies that this specific TC explains 20% of the TWS signal, is this correct? This needs more attention and maybe cutting out dominant TCs below a meaningful threshold.

Response: Thank you for your thoughtful comment. We indeed adopt the maximum correlation coefficient as the dominant TC. We also agree with your comment, and the situation mentioned above could occur in data processing. However, the pixel is independent each other. For each pixel, we could extract the maximum correlation coefficient between TWS and TCs, but we could not obtain the area proportion of each dominant TC during extraction process. Therefore, we adopted maximum correlations to interpretation, and we also discussed this uncertainty in discussion section of our revised manuscript.

(26) Section 4.1 repeats mainly the interpretation of the results section. The last paragraph does not provide any scientific insights in terms of a discussion.

Response: Thank you for your comment. We have reorganized the discussion section according to the both reviewers' comments in our revised manuscript.

(27) Section 4.2 is a description of the TC and in last two sentences it is stated that those TCs are impacting TWS. The reader does not have a much better idea how TWS is affected. And yes, there are methodological questions to solve.

Response: Thank you for your comment. We have added the possible impacts of TCs on TWS according to reviewers' comments in our revised manuscript.

(28) Line 297 f: what is meant with TWS dynamics attributions? I fully agree that coupled human-natural approaches have to be done to better understand to which part TWS dynamics are due to natural or due to anthropogenic variations. This could be then connected with a link to TCs.

Response: Thank you for your comment. We have revised the statement in our revised manuscript. The coupled human-natural model is a promising and challenging issue that need pay more attention in our future work.

(29) The arrangement of Figures is not consistent. Fig 2f is referred to before 2c-e, Figure S6 is referred to before referring to S3 etc. Please follow the journal guidelines which improves the readability. It seems that Fig S6 is the same like Fig 2f – is there any reason for this repetition? Fig. 2e is not referred to in the manuscript.

Response: Thank you for your comment. We have reproduced all figures, and rearranged the sequence of figures in our revised manuscript. We have attached all figures at the end of this response.

(30) Fig 1 and lines ~75: sources are missing for definition of humidity and for area equipped for irrigation

Response: Thank you for your comment. We have supplemented the sources for definition of humidity and for area equipped for irrigation in figure caption.

(31) Fig 2a and b and line 149 ff: I try to make sense out of the numbers and colours. TWS trend seems to be a magnitude larger then precipitation trend. How does a precipitation change of < 1 mm/yr can be the cause for 10

to 20 mm tws change? Precipitation can be a cause, yes, but if the numbers are correct, then I cannot agree that this is the reason and similarly I not agree that there where the pattern looks differently, human impact is the (only) reason. This needs by far more discussion and thorough analysis. From Table S1 some differences are visible for the two Mascon solutions. I suggest to display the two Mascon solutions in Fig 2. The regions in Table S1 could get names.

Response: Thank you for your comment. We feel sorry for the mistake in trend analysis of precipitation in our former version of manuscript, we have recalculated and reproduced the spatiotemporal changes of precipitation over the study area (Figure 3).

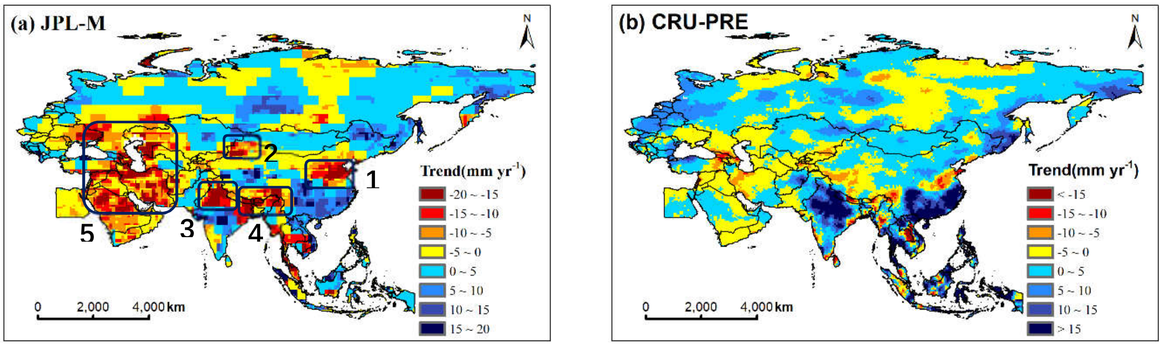

Figure 3: Spatiotemporal changes in TWS as obtained from GRACE (a) and precipitation as obtained from CRU (b) across the Asian and Eastern European regions during 2002-2017. The trend is obtained from the removed seasonal cycle time series.

(32) Fig 2c: check spelling of header text

Response: Thank you for your careful comment. We have revised the spelling of header text in our revised manuscript.

(33) Fig 2f: a legend is missing, and I can only see 4 lines and a mess of shaded area which does not allow any meaningful assessment. Please re-arrange (e.g. splitting it up to 5 single plots with same Y-axis) and it would be meaningful to use month/years for x-axis.

Response: Thank you for your comment. Since this figure mainly presented the TWS trend for five hotspots, which is similar to the figure 5 (see below). Therefore, we have deleted this figure in our revised manuscript.

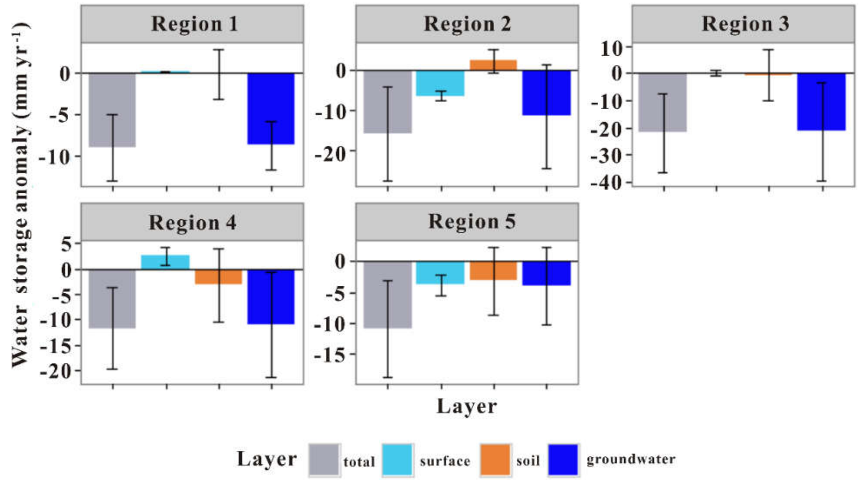

Figure 5: Contributions of different hydrological storages to TWS changes in five hotspots. Uncertainties represent the 95% confidence intervals.

(34) Fig 3: Labelling of Y-Axis with “Water loss” and then negative values – does it imply a water gain? Please name it more meaningful.

Response: Thank you for your comment. We have rectified this mistake, and replaced “water loss” of “water storage anomaly” in our revised manuscript.

(35) Fig 4: what can be seen at both axis? It seems that the months are not consecutive (If I interpret it correctly as spring season), then drawing a solid line through it is misleading.

Response: Thank you for your useful comment. We have aggregated monthly data to yearly data in our revised manuscript (Figure 6).

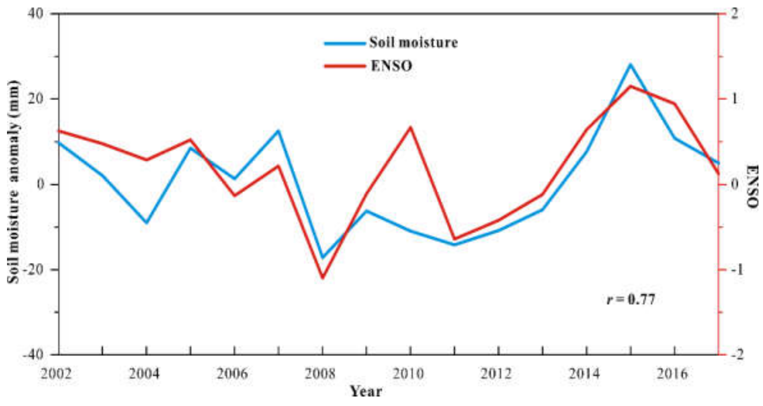

Figure 6: The residual time series of spring soil moisture and associated ENSO in region 3 during 2002-2017.

(36) Fig S1: unit for Y-Axis is missing. I suggest to use month/years instead of month numbers. Why does the time series ends ~at month 165 whereas the other figures are ending at month ~177/181?

Response: Thank you for your comment. The total study period is during April 2002~June 2017, but we use full years for comparison between 2003 and 2016, therefore the time series is during 1~168. We have reproduced the figure by using month/year (Figure S1).

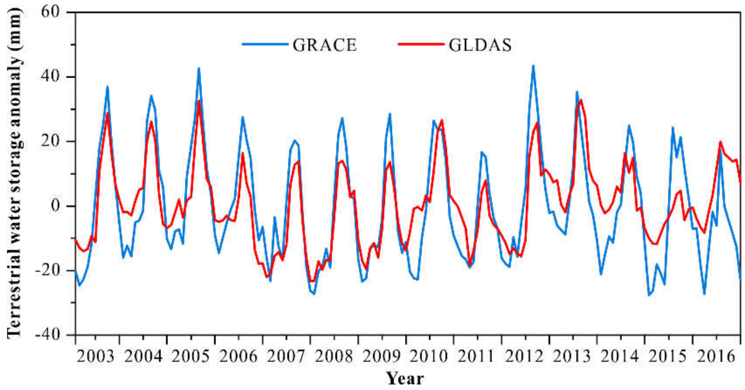

Figure S1. Comparison between GRACE observed terrestrial water storage and GLDAS simulated terrestrial water storage by summing canopy water, four layers soil moisture and snow equivalent water over the Asia and Eastern Europe region during 2003~2016.

(37) Fig S3: what is shown at X- and Y-Axis?

Response: Thank you for your comment. We have reproduced this figure in our revised manuscript (Figure S4).

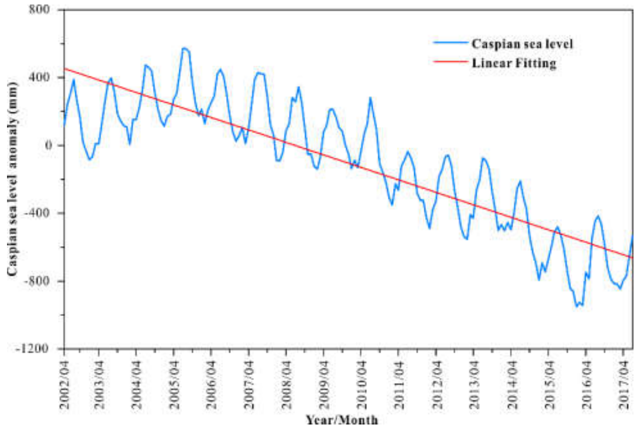

Figure S4. Changes in Caspian Sea Level during 2002-2017.

(38) I have not checked if the references are listed in the reference list and vice versa, and also have not checked the reference list itself.

Response: Thank you for your comment. We have carefully read the following papers, and properly cited them in our revised manuscript.

References

Döll, P., Müller Schmied, H., Schuh, C., Portmann, F. T., & Eicker, A. (2014). Global-scale assessment of groundwater depletion and related groundwater abstractions: Combining hydrological modeling with information from well observations and GRACE satellites. Water Resources Research, 50(7), 5698–5720.https://doi.org/10.1002/2014WR015595

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Revised figures

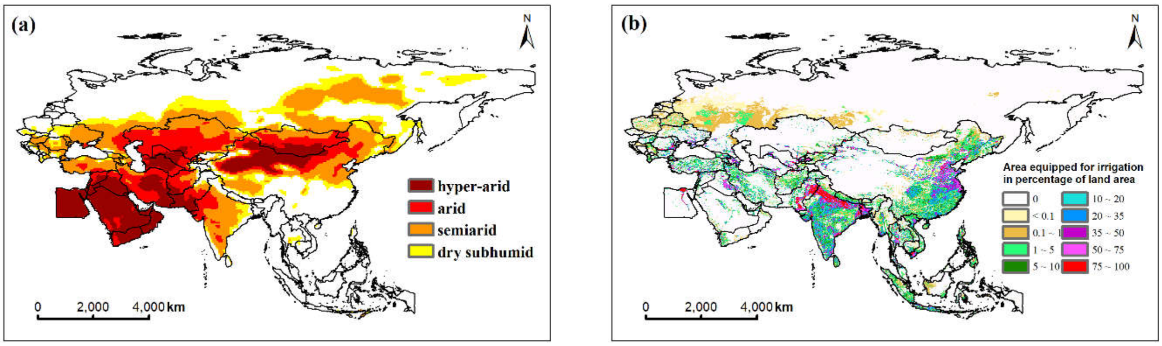

Figure 1: Boundary of the Asian and Eastern European regions. Panel (a) is the spatial distribution of arid and semiarid areas based on averaged aridity index during 2002-2017. The aridity index is calculated based on the ERA-Interim dataset downloaded from European Centre for Medium-Range Weather Forecasts. Panel (b) is the percentage area of irrigated land across the study area. The percentage area of irrigated land dataset is derived from Food and Agriculture Organization of the United Nations.

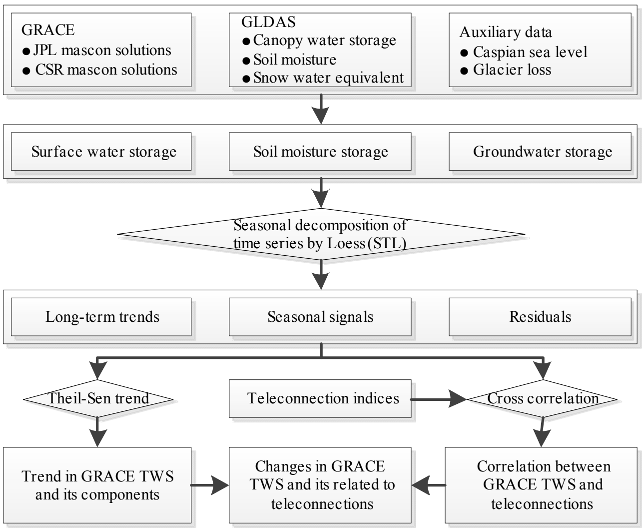

Figure 2: Methodology flow diagram of data processing in this study.

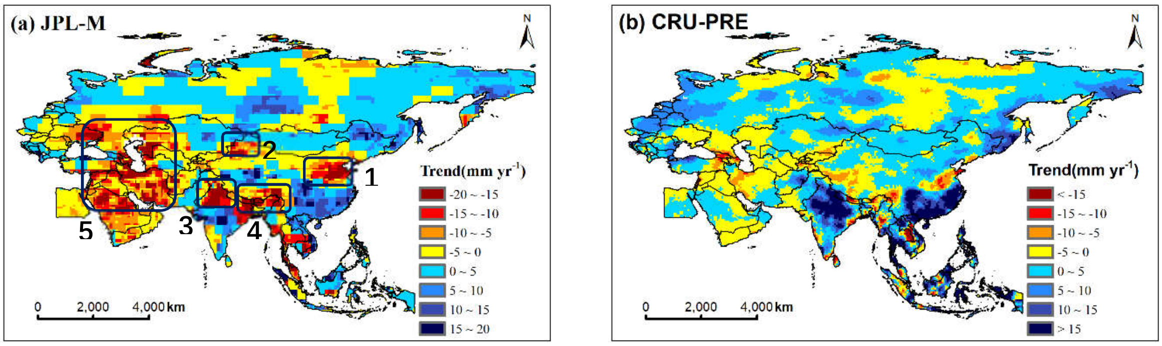

Figure 3: Spatiotemporal changes in TWS as obtained from GRACE (a) and precipitation as obtained from CRU (b) across the Asian and Eastern European regions during 2002-2017. The trend is obtained from the removed seasonal cycle time series.

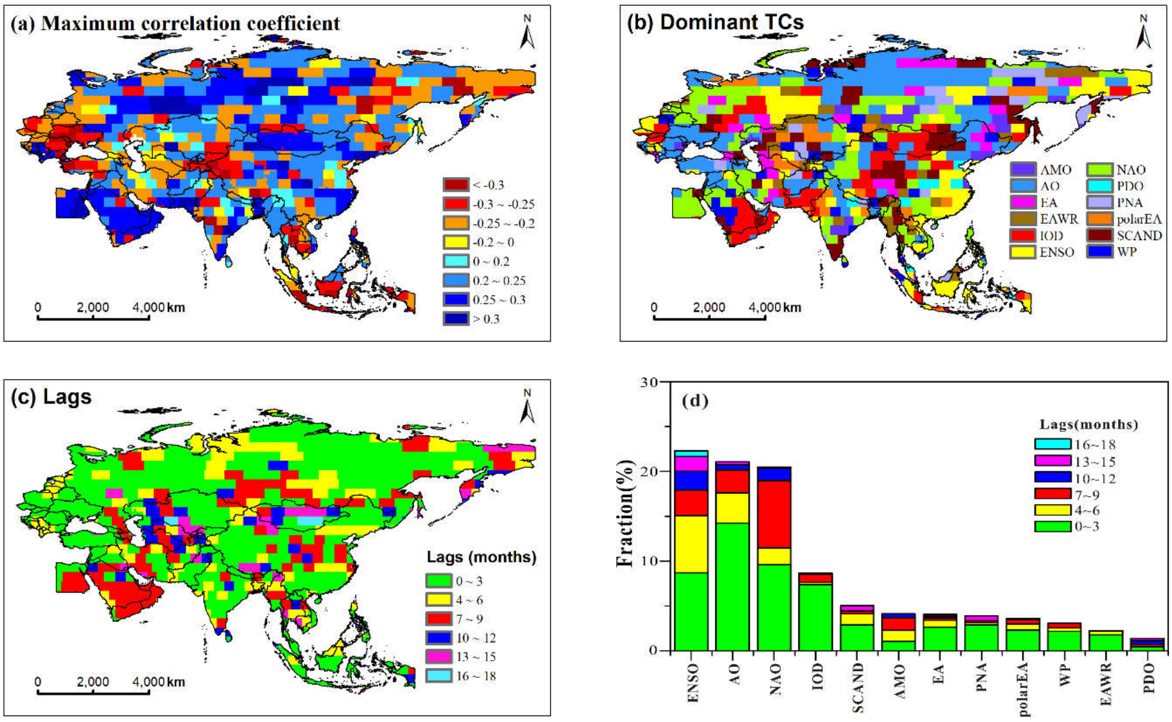

Figure 4: Spatial distribution of cross correlation analysis between TWS and teleconnection indices. (a) Spatial pattern of maximum correlation coefficients between TWS and teleconnection indices. (b) Spatial pattern of teleconnections that can best represent TWS variations. (c) Spatial pattern of teleconnection lag time. (d) Proportion of the area dominated by each teleconnection and its corresponding time lags. The maximum lag in the correlation analysis was limited to 0~24 months (significance threshold: |r| > ~0.15 given a significant level = 0.05 and numbers of time series = 183).

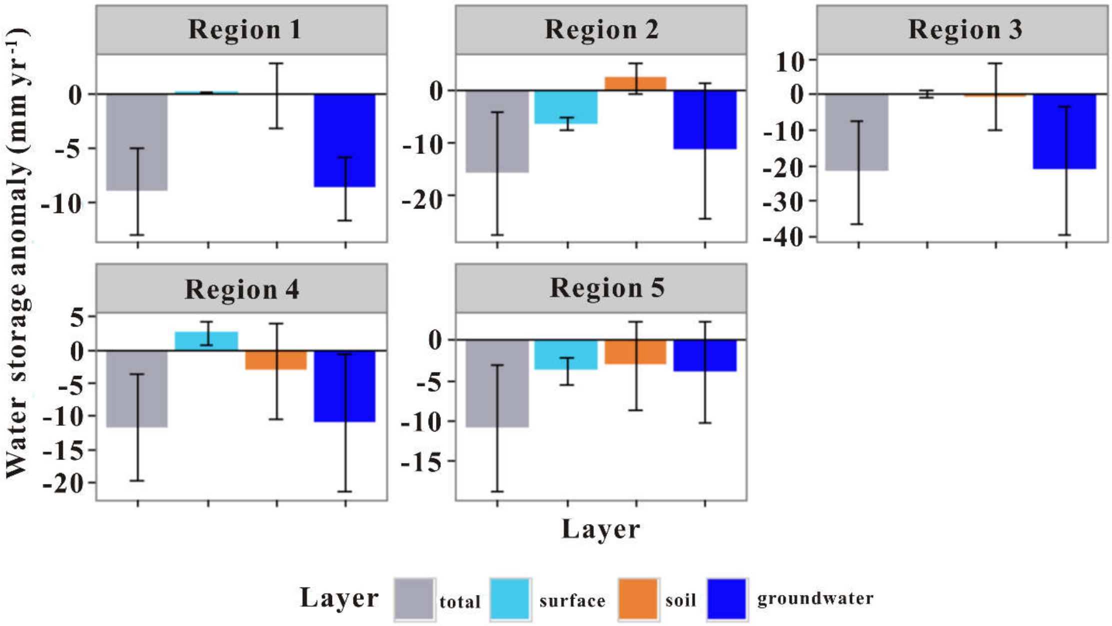

Figure 5: Contributions of different hydrological storages to TWS changes in five hotspots. Uncertainties represent the 95% confidence intervals.

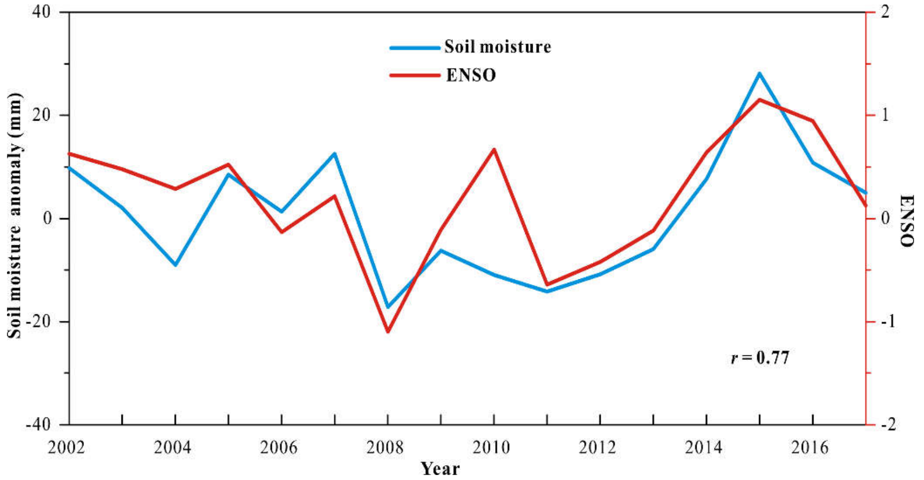

Figure 6: The residual time series of spring soil moisture and associated ENSO in region 3 during 2002-2017.

Table:

Table 1: Descriptions of datasets used in this study

Datasets	**Variables**	**Time span**	**Resolution**	**Source**
GRACE	JPL-M	2002-2017	monthly and 0.5°	The Jet Propulsion Laboratory (Watkins et al., 2015) and the Center for Space Research (Save et al., 2016)
	CSR-M			
GLDAS	Canopy	2002-2017	monthly and 0.25°	The Global Land Data Assimilation System data (Rodell et al., 2004)
	Soil moisture			
	Snow water			
Lakes	Caspian sea	2002-2017	ten days and site	The Database for Hydrological Time Series of Inland Water (Schwatke et al., 2015) and Hydroweb (Crétaux et al., 2011)
	Aral Sea (East)			
	Aral Sea (West)			
	Aral Sea (North)			
Glacier	Tien Shan	2000-2016	year and regional	Literature (Brun et al., 2017)
	Hindu Kush			
	Spiti Lahaul			
	East Nepal			
	Bhutan			
	Nyainqentanglha			
Teleconnections	AO, NAO, EA, EAWR, WP, polarEA, PNA, IOD, AMO, PDO, ENSO, SCAND	2002-2017	monthly and global	The Climate Prediction Center of the U.S. National Oceanic and Atmospheric Administration

Response to referees' comments (hess-2019-281)

We would like to thank the reviewers for their professional, detailed and constructive comments, which improved our manuscript considerably. We have carefully revised the manuscript following their comments point by point. Our revisions and explanations have been inserted in blue, and all amendments are also highlighted in the version of revised manuscript. Additionally, the writing of our revised manuscript are also under carefully editing by English native speaker with specialized in hydrology.

Anonymous Referee #2

The manuscript titled "Widespread decline in terrestrial water storage and its link to teleconnections across Asia and Eastern Europe" by Liu et al., has identified an interesting research gap of analyzing the linkage between teleconnections (TCs) with terrestrial water storage (TWS) in Asia and Eastern Europe. They have utilized comprehensive set of TCs for the study. The TWS has been abstracted from GRACE observations. The TWS is partitioned using GLDAS to generate surface water (SW), soil moisture (SM) and groundwater. The TWS components are then de-seasonalized. This is followed by spatiotemporal trend analysis, comparison analysis with TCs and dissection of each TWS component's contribution to TWS.

Although the manuscript embeds a promising research topic, the level of write up lags far behind the study done which in turn lags behind the research gap stated. The manuscript lacks crisp, clear messages. Most of the time this is due to poor sentence structure and grammar. The reader has to infer what the authors are trying to state or sometimes even conclude. I would not recommend to accept the manuscript in its current form and structure. I would suggest the following major revisions to the authors, if the editor decides to move the process forward.

Response: Thank you very much for your thoughtful and careful comments, which have significantly improved our manuscript. We have substantially revised our manuscript point by point based on reviewers' comments in our revised manuscript.

Major Comments

(1) It is mentioned that the lead author wrote the manuscript with contributions from all others. However, there are significant improvements required in the sentences, paragraphs and information sequence structure. This shows the manuscript was not sufficiently revised before submission. In its current form, the manuscript doesn't facilitate an uninterrupted flow.

Response: Thank you for your comment. We feel sorry for the confusion and inconvenience we have caused to you. We have carefully modified the structure, paragraph and sentence of the manuscript.

(2) Tabulation of data information and a flow diagram of data processing are necessary in the section "Data". It might be a better idea to make an overall methodology flow diagram that includes this.

Response: Thank you for your constructive comment. We have added a table with data information (Table 1), and we also supplemented the flow diagram of overall methodology in our revised manuscript (Figure 2).

Table 1: Descriptions of datasets used in this study

Datasets	**Variables**	**Time span**	**Resolution**	**Source**
GRACE	JPL-M	2002-2017	monthly and 0.5°	The Jet Propulsion Laboratory (Watkins et al., 2015) and the Center for Space Research (Save et al., 2016)
	CSR-M			
GLDAS	Canopy	2002-2017	monthly and 0.25°	The Global Land Data Assimilation System data (Rodell et al., 2004)
	Soil moisture			
	Snow water			
Lakes	Caspian sea	2002-2017	ten days and site	The Database for Hydrological Time Series of Inland Water (Schwatke et al., 2015) and Hydroweb (Crétaux et al., 2011)
	Aral Sea (East)			
	Aral Sea (West)			
	Aral Sea (North)			
Glacier	Tien Shan	2000-2016	year and regional	literature (Brun et al., 2017)
	Hindu Kush			
	Spiti Lahaul			
	East Nepal			
	Bhutan			
	Nyainqentanglha			
Teleconnections	AO, NAO, EA, EAWR, WP, polarEA, PNA, IOD, AMO, PDO, ENSO, SCAND	2002-2017	monthly and global	The Climate Prediction Center of the U.S. National Oceanic and Atmospheric Administration

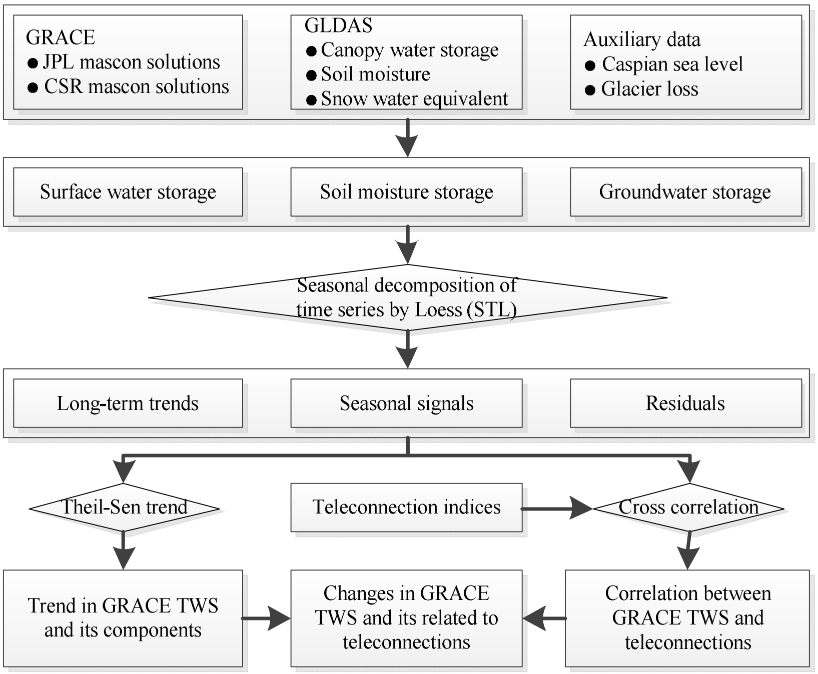

Figure 2: Methodology flow diagram of data processing in this study.

(3) There is no background on TCs and subject matter of the manuscript in regards to the study area in the section "study area".

Response: Thank you for your comment. We have added the background on TCs and subject matter of our manuscript in the section of “study area” as follows. The Asian and Eastern European regions, a total of 54% of the area is arid and semiarid, are located between latitudes 6°S and 56°N and longitudes 4°E and 109°E (Figure 1a). These regions are the most densely populated regions in the world, sustaining nearly half of the global population and contain some of the largest and most intensively irrigated lands of the world (Figure 1b). The freshwater availability in these water-limit regions are essential to food and water security and hence sustainable economics. Notably, surface freshwater is critically limited in these regions (Wang, 2018). The amount of available freshwater in these regions are highly dependent on precipitation and temperature, which are influenced intensively by the Northern Hemisphere atmospheric circulation patterns and the coupled ocean-atmosphere patterns (i.e., teleconnections). The spatial explicit analysis of the impact of teleconnections on freshwater availability in these regions can be studied to provide a simple framework for understanding the complex response of freshwater availability to global climate change.

(4) Although the subtopic headings of results section are clear, the content is very poorly structured and sequenced. Smooth reading flow is missing.

Response: Thank you for your comment. We have substantially revised the sentences and structure of our manuscript according to the comments in our revised manuscript.

(5) Although the subtopic headings of discussion section are clear, the content is very poorly structured and sequenced. For an instance, in section "4.2 Possible mechanisms of TC influence on TWS variability", only the dominant TC and their role in the regions are mentioned. However, the result from this study and discussion on "possible linkage" with these "roles" are missing.

Response: Thank you for your thoughtful comment. We have reorganized the content of this section in our revised manuscript.

(6) The figures and tables of the supplementary section are directly and heavily referred to in the manuscript. This needs to be ratified. The grouping of figures is also not optimal.

Response: Thank you for your comment. We have moved the heavily referred supplementary figures to main body in our revised manuscript.

(7) The preparation of figures and tables is poor and needs significant revising. This includes axes labeling, color combination, color code, headers, data source declaration in the captions.

Response: Thank you for your comment. We have reproduced all the figures and tables in our revised manuscript according to the useful comment. We also attached the revised figures at the end of this response.

Specific Comments (in order of sections of the draft)

1 Introduction

(1) Line 38: May be the gap is mainly in Asia. There are existing studies for Europe. E.g. Rakovec et al. (2016) have already analyzed the TWS anomaly using GRACE in 400 European river basins.

Response: Thank you for your comment. We have carefully read this paper in the revision of the introduction section in our revised manuscript.

(2) Line 42: "...are undergoing intensive..."

Response: Thank you for your comment. We have revised the grammar mistake, and we also carefully check the revised manuscript.

(3) Line 44: mm/y vs mm yr-1 (in abstract). Inconsistent usage of unit format.

Response: Thank you for your careful comment. We have corrected the mistake in our revised manuscript.

(4) Line 63-64: "...and the remainder of the TWS time series..." It's not clear for the reader what this is referring to.

Response: Thank you for your comment. We have paraphrased this sentences to "we use detrended and deseasonalized TWS time series" in our revised manuscript.

2.1 Study Area

(5) Figure 1a: Source/ citation is missing. Color representation for Semi-arid and dry subhumid regions don't have sufficient contrast.

Response: Thank you for your comment. We have reproduced the figure 1. Panel (a) is the spatial distribution of arid and semiarid areas based on averaged aridity index during 2002-2017. The aridity index is calculated based on the ERA-Interim dataset downloaded from European Centre for Medium-Range Weather Forecasts. Panel (b) is the percentage area of irrigated land across the study area. The percentage area of irrigated land dataset is derived from Food and Agriculture Organization of the United Nations.

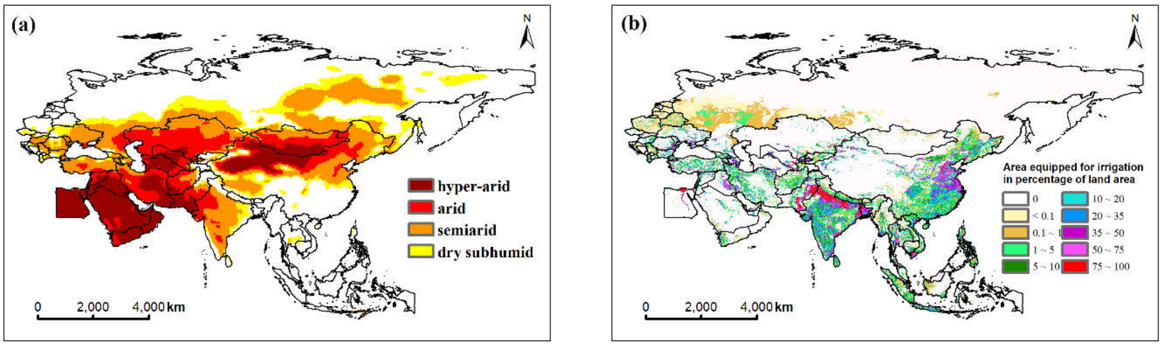

Figure 1: Boundary of the Asian and Eastern European regions.

(6) Line 72: Mount Kilimanjaro is in Africa, not the study area.

Response: Thank you for your comment. We have corrected the mistake in our revised manuscript.

(7) Line 73: The URL link doesn’t have public access. And its mentioning here is also not clear.

Response: Thank you for your comment. We have replaced the URL link of data source citation in our revised manuscript.

(8) Line 75: I couldn’t grasp the usage of "...in this area". Did you mean to say "More importantly, the Asian and Eastern European regions are the most densely populated regions in the world, sustaining nearly half of the global population and contain some of the largest and most intensively irrigated lands of the world"? If so, kindly cite the source.

Response: Thank you very much for your comment. We have revised the sentences according to your useful suggestions and also added the source.

(9) Figure 1b: Source is missing.

Response: Thank you for your comment. We have added the source of Figure 1b in Figure 1 caption as follow in our revised manuscript. The percentage area of irrigated land dataset is derived from Food and Agriculture Organization of the United Nations.

(10) Line 75-77: Split long sentence to two. Also kindly include the source.

Response: Thank you for your kindly comment. We have rewritten this paragraph and deleted this sentence in our revise manuscript.

(11) Line 69-77: The research gap of comprehensive TWS-TC correlation would need some background on TCs in the study area. This is missing and should be discussed in more detail in this section. If the manuscript space permits, additional map/s depicting the TCs and their role in the regions would improve the clarity of the topic to the readers.

Response: Thank you for the constructive comment. We have added the background on TCs and subject matter in the of “study area” section of our revised manuscript.

2.2 Data

(12) Line 79-110: Tabulating the dataset information would be a more efficient way of presenting than the current form. E.g. Line 91 mentions the exact same thing mentioned in previous sentence just adding additional spatial information. This is followed by the web URL for the dataset. Tabulation of info would be the perfect solution here.

Response: Thank you for your constructive comment. We have added the dataset table in our revised manuscript.

(13) Line 92: Avoid using direct URLs for data reference. There are better ways to cite datasets.

Response: Thank you for your comment. We have replaced the URLs of datasets citation in our revised manuscript.

(14) Line 93: Bicubic interpolation doesn’t preserve the mass while resampling. Mass conservative remapping is advised (e.g. remapcon operator of CDO)

Response: Thank you for your comment. We have attempted different resampling methods in revision process,

i.e. nearest neighbor and bilinear interpolation. We adopted the nearest neighbor interpolation method in our revised manuscript in order to preserve the original data values. Thank you for your advice. The climate data operators (CDO) is a powerful tool in time series data set.

(15) Line 94-97: This sentence has 62 words! This doesn't help readability of the manuscript. Kindly break into shorter sentences. One message per sentence.

Response: Thank you for your comment. We have rewritten this paragraph and split this long sentence into short sentences in our revised manuscript.

(16) Line 98: The x-axis header for Figure S1 is missing. Moreover, the x-axis is not uniform across figures S1, S2, S3, S6.

Response: Thank you for your comment. We have reproduced all figures in our revised manuscript and supporting information. We have attached these figures at the end of this response.

(17) Line 101: "... by deducting..."

Response: Thank you for your comment. We have revised the grammar mistake in our revised manuscript, and we also carefully checked the revised manuscript.

(18) Line 79-110: Apart from tabulating the dataset information, the data assimilation approach would be much easier presented as flow diagram.

Response: Thank you for your constructive comment. We have provided the methodology flow diagram of the detail data processing and analysis in our revised manuscript.

(19) Line 105-110: This can go into the data table. However, some elaboration of these 12 TCs in regards to the study area is missing. I would suggest to switch the position of 2.1 and 2.2. With this new sequence, the authors can provide further insight on TCs from view point of study area in the section "Study Area".

Response: Thank you for your comment. We have supplemented briefly elaboration of these 12 TCs in data section of the revised manuscript as follows. The term teleconnection may refer to patterns arising from the internal variability of the atmosphere only also from the coupling between the air and the ocean. In this study, we analyze the TCs that dominate climate variability in the Northern Hemisphere, namely, Arctic Oscillation (AO), North Atlantic Oscillation (NAO), East Atlantic (EA), East Atlantic/Western Russia (EAWR), Scandinavia (SCAND), Polar/Eurasia (polarEA), West Pacific (WP), Pacific/North America (PNA), and four important atmosphere-ocean coupled variability patterns that influence global climate, the Indian Ocean Dipole (IOD), the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO), and ENSO (Zhu et al., 2017). The 8 first indices refer to Northern Hemisphere atmospheric circulation patterns. These 8 first indices were calculated for region 20°N- 90°N using a rotated principal component analysis (RPCA) of monthly mean standardized 500-mb height anomalies fields (Barnston and Livezey,

1987). The IOD is defined by the difference in sea surface temperature between two areas – a western pole in the western India Ocean (50~ 70° E, 10° S~ 10° N) and an eastern pole in the eastern Indian Ocean (90~110° E, 10° S~ EQ). The IOD affects the climate of Asia, and is a significant contributor to rainfall variability in this region (Saji et al., 1999). The AMO and PDO index are defined as the leading principal component of the North Atlantic Ocean (0-65°N, 80°W-0°E) and the North Pacific Ocean (poleward to 20°N) monthly sea temperature variability, respectively (Enfield, 2001; Bond, 2000). ENSO is the most important coupled ocean-atmosphere phenomenon driving global climate variability. We adopted the monthly Multivariate ENSO Index (MEI) in this study, which takes into consideration variability both in the atmosphere and in the ocean (Wolter and Timlin, 2011).

2.3 Methods

2.3.1 Time series decomposition

(20) Line 113: The first sentence here is out of subject. The current subject is decomposition and this sentence is about trend analysis (belongs to section 2.3.2?)

Response: Thank you for your comment. We have moved this sentence to section 2.3.2 in our revised manuscript.

(21) Line 113-124: Revise the order of the sentences and info. Not in optimum order.

Response: Thank you for your comment. We have revised the paragraph in our revised manuscript.

(22) Line 118: STL is a robust method? Then cite the papers who have proven this method to be robust.

Response: Thank you for your comment. We have added the citations in our revised manuscript.

(23) Line 118: "for detecting non-linear time series in trend estimates". What do you mean? The sentence doesn’t make sense to me.

Response: Thank you for your comment. We have paraphrased this sentence in our revised manuscript.

(24) Line 123-124: Refer to previous publication of this journal to understand how to cite in such situation.

Response: Thank you for your comment. We have modified the citation in our revised manuscript.

2.3.2 Theil-Sen trend analysis

(25) Line 126: "..the linear trend of .... and precipitation for the ..."

Response: Thank you for your comment. We have revised this sentence based on the useful comment in our revised manuscript.

(26) Line 126: Trend analysis on the deseasonalized time series? or the residuals? I am guessing the first sentence of section 2.3.1 belongs here [??]

Response: Thank you for your comment. Trend analysis in this study is based on the deseasonalized time series. We have revised this sentence in our revised manuscript.

(27) Line 126-127: Break the long sentence into two. Move the second part to the end of the section. In this way

flow of read regarding Theil-Sen trend analysis is maintained.

Response: Thank you for your comment. We have modified this section based on the useful comment in our revised manuscript.

(28) Line 128: "... of the Theil-Sen trend analysis is ..."

Response: Thank you for your comment. We have added "analysis" in our revised manuscript.

(29) Line 130: Remove "non-robust". And cite the literature proving this statement.

Response: Thank you for your comment. We have revised this sentence and added citation in our revised manuscript.

(30) Line 130: "The TWS trend, ß, for a ..."

Response: Thank you for your comment. We have revised this sentence based on your comment in our revised manuscript.

2.3.3 Cross-correlation analysis

(31) Line 136: TWS or TWS residual?

Response: Thank you for your comment. We have replace TWS of TWS residual, and reorganized this section in our revised manuscript.

(32) Line 139: Move the "," to the end of the equation. At the moment its on the denominator.

Response: Thank you for your comment. We have revised this mistake in our revised manuscript.

(33) Line 139: What is the meaning of the symbol Tau here? Is it the lag?

Response: Thank you for your comment. The symbol Tau is the time lag, and we have added the explanation in our revised manuscript.

(34) Line 140-141: "auto-covariace"?

Response: Thank you for your comment. We have revised this word in our revised manuscript.

(35) Line 142: Why between 0 and 24? Reason, in brief, required. Moreover, can cross correlation have value greater than 1?

Response: Thank you for your comment. The value of cross correlation coefficient lies between -1 and +1. We have corrected the statement in our revised manuscript. Additionally, the multiple TCs could reflect different influence of atmosphere and ocean variability on TWS from short-term to long-term. For example, the impact of AO and NAO have a relatively high-frequency variability on TWS. Therefore, we adopt the lag of 0-24 month in current study in order to address the different time scale responses of TCs on TWS.

(36) Line 143-146: Break the sentence to get one message per sentence.

Response: Thank you for the comment. We have broken this long sentence into short sentences in our revised manuscript.

3 Results

3.1 Spatiotemporal changes in TWS

(37) Line 149: Mention that both JPL-M and CSR-M showed similar spatiotemporal pattern to begin with. Then let the reader know that the values will be referred to JPL-M.

Response: Thank you for your comment. We have supplemented these sentences in first of section 3.1 in our revised manuscript.

(38) Line 152: The 5 hotspots are clearly shown in Figure 2a. This should be included in the reference illustrations.

Response: Thank you for your comment. We have added the reference illustration in our revised manuscript.

(39) Line 152: Figure 2f doesn't have color code. Unit of time is missing. Time axis with years as axis tick labels would enhance clarity.

Response: Thank you for your comment. Since this figure mainly presented the TWS trend for five hotspots, which is similar to the figure 5. Therefore, we have deleted this figure in our revised manuscript.

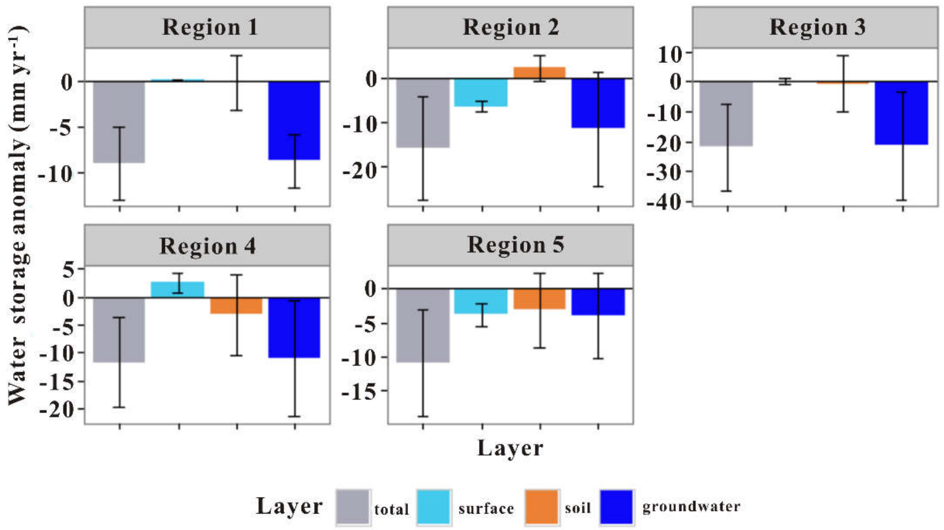

Figure 5: Contributions of different hydrological storages to TWS changes in five hotspots. Uncertainties represent the 95% confidence intervals.

(40) Line 153: Figure S6 doesn't have color code.

Response: Thank you for your comment. We have reproduced the figure in our revised manuscript.

(41) Line 154: Precipitation is in figure 2b, not 2c.

Response: Thank you for your comment. We have corrected this mistake in our revised manuscript.

(42) Line 157: Precipitation is in figure 2b, not 2c.

Response: Thank you for your comment. We have corrected this mistake in our revised manuscript.

(43) Line 158: How is this "within" Rodell's findings? The estimates are completely contrasting each other. Plus, the reasoning is not convincing and/or explained properly.

Response: Thank you for your comment. We have rewritten this sentence in our revised manuscript.

(44) Line 162: -73.2 mm y^{-1} is out of range for figure 2a.

Response: Thank you for your comment. The trend in Figure 2a (Figure 3a in revised manuscript) is the changes in terrestrial water storage over the study area (equivalent water depth), whereas the trend of -73.2 mm y^{-1} is the water level variation of the Caspian Sea.

3.2 Influence of TC indices on TWS variability

(45) Line 174: Which section of the multi-plot Figure 2? Revise the header and legend header of figure S5 to something more explicit. In caption of Figure S5, replace "phase shift" by "lag". Usage of same terminology maintains the flow of reading. And what are the symbol alpha and "n" in the caption?

Response: Thank you for your comment. We have reproduced these figures, and added clarifications in figure captions.

(46) Line 175: "... and NAO have a significant area of influence on TWS variability."

Response: Thank you for your comment. We have revised the sentence according to you suggestion in our revised manuscript.

(47) Line 181: Resolve the structural error. Two sentences or one?

Response: Thank you for your comment. We have revised the structural error in our revised manuscript.

(48) Line 189: "Proportions of time .... Figure 2d". This sentence should be the starting sentence of this paragraph.

Response: Thank you for your comment. We have revised this sentence according to you useful suggestion in our revised manuscript.

(49) Line 190: Tibetan plateau and Mongolia have more pixels of longer lags than SE Asia.

Response: Thank you for your comment. We have rewritten this sentence in our revised manuscript.

3.3 Contributions of water storage components to TWS

(50) Line 194: The first sentence is concluding findings. Thus, it is more suitable to be placed towards the end of the section.

Response: Thank you for your comment. We have moved the first sentence to the end of the section in our revised manuscript.

(51) Line 195: The hotspots have been well established in the manuscript and doesn’t need the reference to Figure 2a every time.

Response: Thank you for your comment. We have deleted the reference of hotspots in our revised manuscript.

(52) Line 195: "Groundwater depletion dominates the contribution to TWS loss in region 1..."

Response: Thank you for your comment. We have revised this sentence in our revised manuscript.

(53) Line 197: "Similar results were observed in northwest..."

Response: Thank you for your comment. We have revised this sentence in our revised manuscript.

(54) Line 210: The term "sea level" could be confused with the world mean sea level. Suggested rephrasing: "...Caspian Sea with a decrease in its water level elevation by -73.2 mm y^{-1}..."

Response: Thank you for your comment. We have rephrased this sentence according to your useful suggestion in our revised manuscript.

3.4 Divergent response of water storage components to TCs

(55) Line 217: The first sentence is concluding findings. Thus, it is more suitable to be placed towards the end of the section.

Response: Thank you for your comment. We have moved the first sentence to the end of the section in our revised manuscript.

(56) Line 222: "...is a synthesis signal i.e. its trend ...". "... different ways. Furthermore, the groundwater ..."

Response: Thank you for your comment. We have revised this sentence in our revised manuscript.

(57) Line 223: "...which indicates lower correlation..."

Response: Thank you for your comment. We have replaced the word "less" of "lower" in this sentence in our revised manuscript.

(58) Line 225: Reference to a figure or table missing

Response: Thank you for your comment. We have added the reference in this sentence in our revised manuscript.

4 Discussion

4.1 Comparison of our results to previous studies

(59) Line 235-257: Please be clear about which region are you talking about. If you start with "Region 1 shows ..." then its clear that the information corresponding to that region (1, 3 and 4) else its hard to follow (regions 2 and 4).

Response: Thank you for your comment. We have rewritten this section in our revised manuscript as follows. We investigate the spatiotemporal trend of TWS and its components over Asia and Eastern Europe region during 2002-2017. The spatial pattern and trend of TWS over the study area are consistent with those of previous studies (Humphrey et al., 2016; Scanlon et al., 2016). Our estimate trend (-8.94±3.91 mm yr^{-1}) of TWS in region 1 is within that of previous studies in this region (22±3 mm yr^{-1} during 2003-2010) (Feng et al., 2013; Tangdamrongsub et al., 2018). The discrepancies may be stemmed from the inconsistent of study period and spatial domain. Due to a long-term warm and dry climate and intensive anthropogenic activities (agriculture, industry, and urbanization), the groundwater in region 1 has been overexploited since the 1970s, and more than 70% of the groundwater exploitation is used for regional irrigation (Wang et al., 2007). The rate of groundwater loss rate in region 3 (-21.35 mm yr^{-1}) was also comparable with a previous study in region 3, with approximately 40±10 mm yr^{-1} from August 2002 to October 2008 (Rodell et al., 2009). As

Indian agriculture leads the world in total irrigated land by consuming ~85% of the utilizable water resources (Salmon et al., 2015; Panda et al., 2016), a concluding consensus has been reached that the dramatic decline in TWS is mainly due to the overexploitation (extraction exceeding recharge) of groundwater for irrigation (Shamsudduha et al., 2019). Although precipitation in region 3 shows an increasing trend during the GRACE period, the rapid depletion of TWS in northwest India induced by unsustainable consumption of groundwater for irrigation and other anthropogenic uses has attracted worldwide attention because it is a major threat to India's sustainability (Rodell et al., 2009; Panda et al., 2016). Region 4 in our study is heavily irrigated (Figure 1), so intensive irrigation is likely to induce groundwater decline (-11.00±10.43 mm yr^{-1}). The increase in SW induced by melt water from mountains (Brun et al., 2017) was offset by the decrease in soil water that may be related to the decrease in precipitation (Figure 3b). For region 2, the rapidly melt of the glaciers of Tien Shan Mountain accelerate an increase in the loss of water resources, since the glacial meltwater will provide additional water that was lost to rivers or evaporation (Jacob et al., 2012). The negative trend in TWS indicates that water demand is larger than supply in region 2, which can be attributed to both continuous withdrawal of groundwater and extensive evaporation in the endorheic basin (Rodell et al., 2018). However, the increase in precipitation is expected to offset a certain portion of water losses in region 2. Previous studies also documented that the widespread decline in TWS in region 5 is attributed to the overreliance on groundwater for domestic and agricultural needs due to human-made dams in addition to the sharply surface water loss (Voss et al., 2013; Joodaki et al., 2014; Rodell et al., 2018). These existing analyses indicate that the widespread declines in TWS and its hydrological components are primarily attributed to the intensive overextraction of groundwater or warm-induced surface water loss, which are consistent with our findings in this study.

(60) Line 258-260: Break the sentence to get one message per sentence.

Response: Thank you for your comment. We have reorganized this paragraph in our revised manuscript.

(61) Line 260-263: Break the sentence to get one message per sentence.

Response: Thank you for your comment. We have reorganized this paragraph in our revised manuscript.

(62) Line 263-264: Revise the sentence for clarity. The concluding sentence should be clear.

Response: Thank you for your comment. We have revised this sentence for clarity in our revised manuscript.

4.2 Possible mechanisms of TC influence on TWS variability

(63) Section 4.2: This is probably the most interesting subtopic of the paper. The writing style should have followed this pattern: 1) result observation at each hotspot, 2) literature on the dominant TC for the hotspot, 3) linking "possible mechanism" between the literature and the results. Currently the section is filled with only 2. There is no linking going on.

Response: Thank you for your constructive comment. We have reorganized section 4.2 according to your comment in our revised manuscript.

4.3 Implications for future hydrological studies

(64) Line 288: "... could explain the variability in TWS in most of the remote and ..."

Response: Thank you for your comment. We have revised this sentence in our revised manuscript.

(65) Line 290: "... variability interacts with human..."

Response: Thank you for your comment. We have revised this sentence in our revised manuscript.

(66) Line 297: "claim" is a very strong word. Moreover, it doesn't make sense especially as the paper hasn't included any prediction or scenario analysis of droughts and heatwaves.

Response: Thank you for your comment. We have replaced the word "claim" of "infer" in our revised manuscript.

(67) Line 300-314: Usage of "First, Second, Third" in paragraph structure requires different approach of writing. Instead, bullet style enumeration of the three recommendations would suit the current sequence and structure of writing i.e. start first bullet with "Withdrawal of ...", and so on.

Response: Thank you for your comment. We have revised the usage of "First, Second, Third" by using bullet style enumeration in our revised manuscript.

5 Conclusions

(68) Line 321: "...component vary from region to region. The ..."

Response: Thank you for your comment. We have revised this sentence in our revised manuscript.

(69) Line 323: "...and regions. This highlights the importance ...."

Response: Thank you for your comment. We have revised this sentence in our revised manuscript.

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RAKOVEC, O., KUMAR, R., MAI, J., CUNTZ, M., THOBER, S., ZINK, M., ATTINGER, S., SCHÄFER, D., SCHRÖN, M. and SAMANIEGO, L.: Multiscale and Multivariate Evaluation of Water Fluxes and States over European River Basins, J. Hydrometeorol., 17, 287–307, doi:10.1175/JHM-D-15-0054.1, 2016.

Response: Thank you very much for all the comments. We have properly cited this paper in our revised manuscript.

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Revised figures

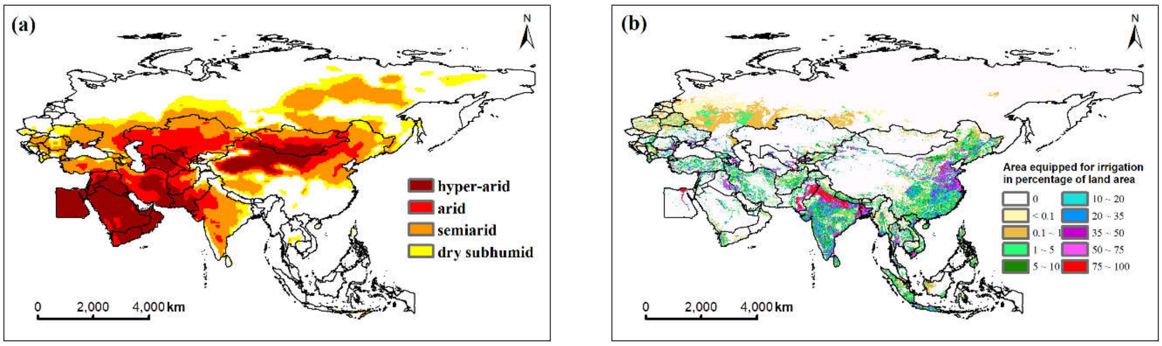

Figure 1: Boundary of the Asian and Eastern European regions. Panel (a) is the spatial distribution of arid and semiarid areas based on averaged aridity index during 2002-2017. The aridity index is calculated based on the ERA-Interim dataset downloaded from European Centre for Medium-Range Weather Forecasts. Panel (b) is the percentage area of irrigated land across the study area. The percentage area of irrigated land dataset is derived from Food and Agriculture Organization of the United Nations.

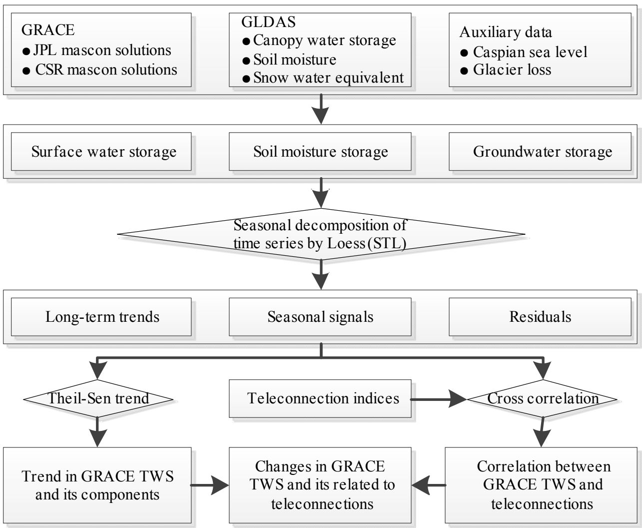

Figure 2: Methodology flow diagram of data processing in this study.

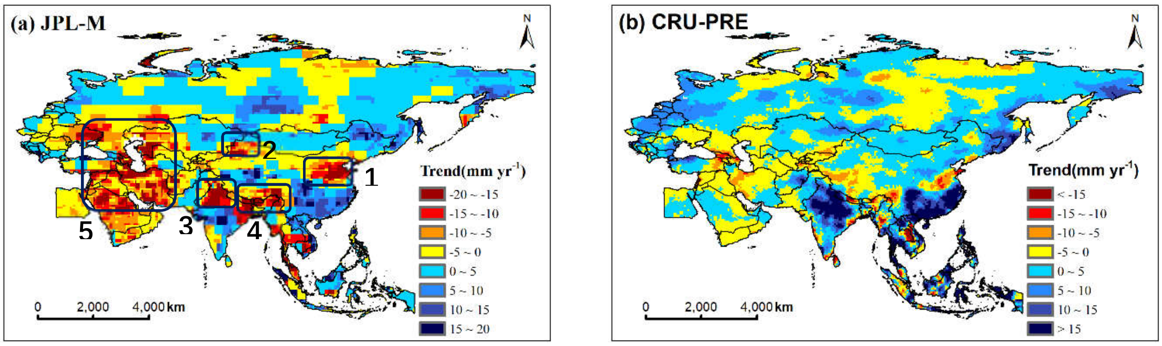

Figure 3: Spatiotemporal changes in TWS as obtained from GRACE (a) and precipitation as obtained from CRU (b) across the Asian and Eastern European regions during 2002-2017. The trend is obtained from the removed seasonal cycle time series.

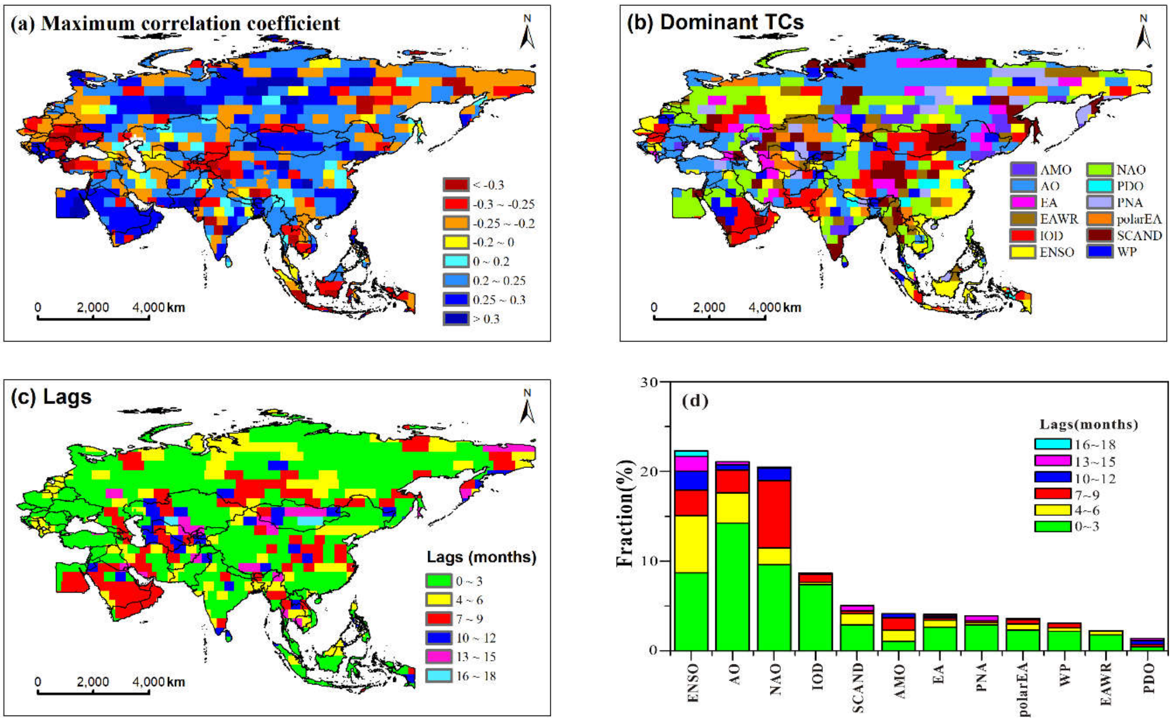

Figure 4: Spatial distribution of cross correlation analysis between TWS and teleconnection indices. (a) Spatial pattern of maximum correlation coefficients between TWS and teleconnection indices. (b) Spatial pattern of teleconnections that can best represent TWS variations. (c) Spatial pattern of teleconnection lag time. (d) Proportion of the area dominated by each teleconnection and its corresponding time lags. The maximum lag in the correlation analysis was limited to 0~24 months (significance threshold: |r| > ~0.15 given a significant level = 0.05 and numbers of time series = 183).

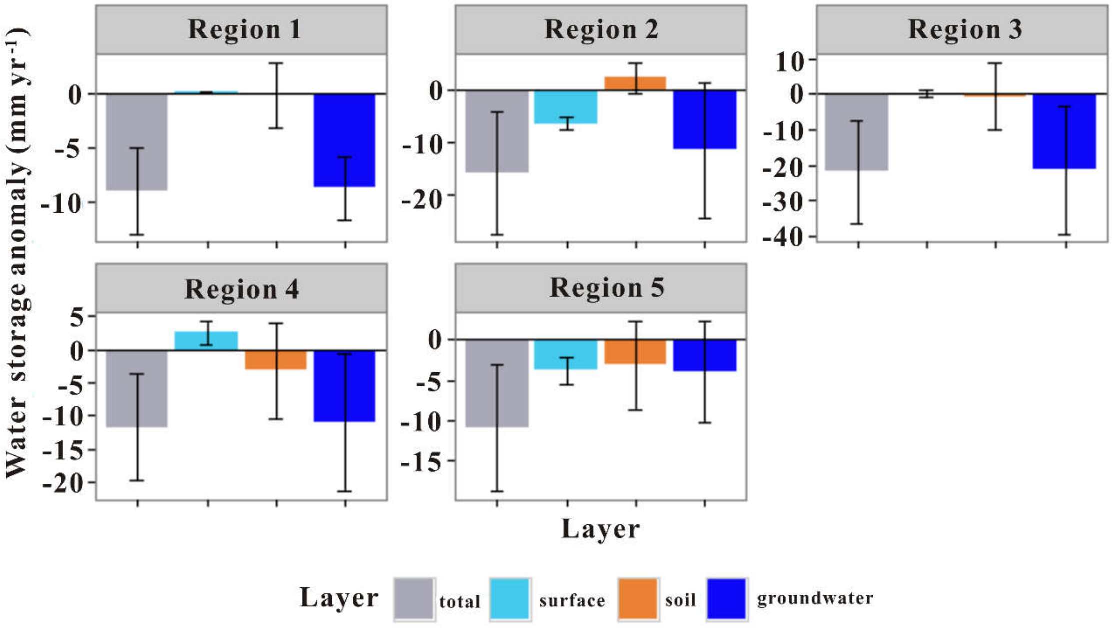

Figure 5: Contributions of different hydrological storages to TWS changes in five hotspots. Uncertainties represent the 95% confidence intervals.

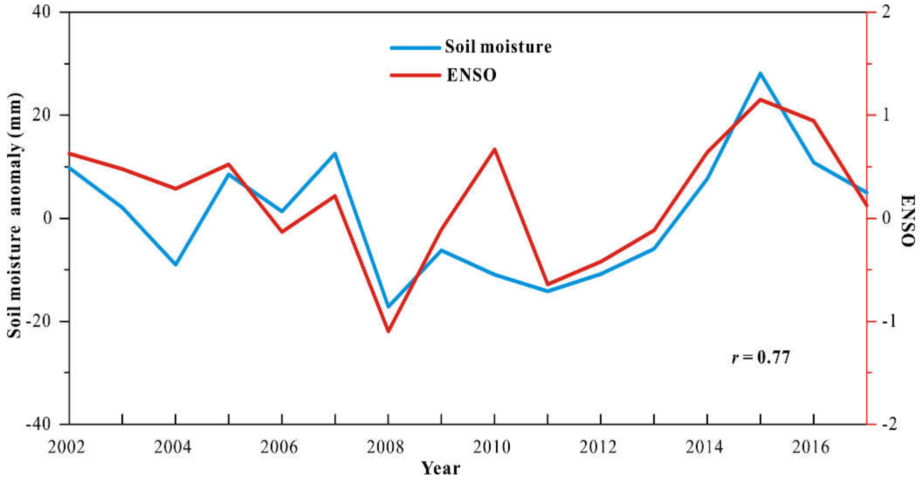

Figure 6: The residual time series of spring soil moisture and associated ENSO in region 3 during 2002-2017.

Table:

Table 1: Descriptions of datasets used in this study

Datasets	**Variables**	**Time span**	**Resolution**	**Source**
GRACE	JPL-M	2002-2017	monthly and 0.5°	The Jet Propulsion Laboratory (Watkins et al., 2015) and the Center for Space Research (Save et al., 2016)
	CSR-M			
GLDAS	Canopy	2002-2017	monthly and 0.25°	The Global Land Data Assimilation System data (Rodell et al., 2004)
	Soil moisture			
	Snow water			
Lakes	Caspian sea	2002-2017	ten days and site	The Database for Hydrological Time Series of Inland Water (Schwatke et al., 2015) and Hydroweb (Crétaux et al., 2011)
	Aral Sea (East)			
	Aral Sea (West)			
	Aral Sea (North)			
Glacier	Tien Shan	2000-2016	year and regional	Literature (Brun et al., 2017)
	Hindu Kush			
	Spiti Lahaul			
	East Nepal			
	Bhutan			
	Nyainqentanglha			
Teleconnections	AO, NAO, EA, EAWR, WP, polarEA, PNA, IOD, AMO, PDO, ENSO, SCAND	2002-2017	monthly and global	The Climate Prediction Center of the U.S. National Oceanic and Atmospheric Administration

Widespread Decline in Terrestrial Water Storage and Its Link to Teleconnections across Asia and Eastern Europe

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Abstract. Recent global changes in terrestrial water storage (TWS) and associated freshwater availability raise major concerns over the sustainability of global water resources. However, our knowledge regarding the long-term trends in TWS and its components is still not well documented. In this study, we characterize the spatiotemporal variations in TWS and its components over the Asian and Eastern European regions from April 2002 to June 2017 based on Gravity Recovery and Climate Experiment (GRACE) satellite observations, land surface model simulations, and precipitation observations. The connections of TWS and global major teleconnections (TCs) are also discussed. The results indicate a widespread decline in TWS during 2002–2017, and five hotspots of TWS negative trends were identified with trends between -8.94 mm yr^{-1} and -21.79 mm yr^{-1}. TWS partitioning suggests that these negative trends are primarily attributed to the intensive over-extraction of groundwater and warm-induced surface water loss, but the contributions of each hydrological component vary among hotspots. The results also indicate that the El Niño-Southern Oscillation, Arctic Oscillation and North Atlantic Oscillation are the three largest, dominant factors controlling the variations in TWS through the covariability effect on climate variables. However, seasonal results suggest a divergent response of hydrological components to TCs among seasons and hotspots. Our findings provide insights into changes in TWS and its components over the Asian and Eastern European regions, where there is a growing demand for food grains and water supplies.

1 Introduction

Terrestrial water storage (TWS), a fundamental component of terrestrial hydrological cycles (Tang et al., 2010), represents the total water stored above and below a land surface (Syed et al., 2008). TWS is composed of surface water (SW), including lakes, snow water equivalent, canopy water and glaciers, soil moisture (SM), and groundwater (GW) storage (Ni et al., 2018; Cao et al., 2019). Changes in TWS are strongly affected by climate change, e.g., drought, floods, prolonged high temperatures, and anthropogenic activities, e.g., abstraction-driven groundwater depletion. Recent TWS information has raised worldwide concerns because of its association with freshwater availability and concerns about the sustainability of global water resources (Creutzfeldt et al., 2012; Meng et al., 2019). Accurate monitoring and quantification of TWS is therefore critical for sustainable water resources management.

Gravity Recovery and Climate Experiment (GRACE) satellites measured global TWS changes from April 2002 to June 2017 (Reager et al., 2009), which provided hydrologists with practical insights at regional and global scales in comparison to in situ measurements (Zhang et al., 2015; Cao et al., 2019). With GRACE data, previous literature has mostly focused on the TWS changes at the basin, regional or continental scale (Syed et al., 2008; Rodell et al., 2009; Long et al., 2013; Creutzfeldt et al., 2015; Zhang et al., 2015; Rakovec et al., 2016; Yi et al., 2016; Ndehedehe et al., 2017; Shamsudduha et al., 2017; Yang et al., 2017; Ni et al., 2018). For instance, Rakovec et al. (2016) analyzed the TWS anomaly using GRACE in 400 European river basins. GRACE data also contributed to the exploration of hydrological storage changes, e.g., glacial mass loss (Jacob et al., 2012; Brun et al., 2017; Huss et al., 2018), lake level and extent changes (Zhang et al., 2013; Zhang et al., 2017), and groundwater depletion (Rodell et al., 2009; Wada et al., 2010; Döll et al., 2014; Long et al., 2016; Feng et al., 2018; Tangdamrongsub, et al., 2018). However, few studies have focused on the contributions of hydrological components to TWS variability at a large scale, particularly in water-limited and densely populated regions (Tapley et al., 2019). Fortunately, two recent global scale studies substantially improved our knowledge by identifying 34 hotspots of TWS changes during 2002–2016 (Rodell et al., 2018) and the changes in global endorheic basin water storage (Wang et al., 2018). The Asian and Eastern European regions, home to half of the world's population and 50% of its arid/semiarid climate areas, are undergoing intensive water threats to agriculture and domestic water needs (Huang et al., 2016) (Figure 1). Most of the countries located within the borders of Asia and Eastern Europe are experiencing water resource shortages caused by low annual precipitation (less than 400 mm yr^{-1}); when the area of these countries are combined, they consequently comprise the largest amount of irrigated land in the world (Rodell et al., 2009). The increasing demand for freshwater and the limited knowledge on the available water resources in this region have become the key challenges to achieving sustainability in these areas (Feng et al., 2013). Therefore, knowledge on the TWS trend and its hydrological components is important for the sustainable development of water resources and food supplies in this region.

The large-scale mode of teleconnection (TC) is an overwhelming factor in regional water resources, modulating the location and strength of storm tracks and fluxes of heat, moisture, and momentum. For example, prominent teleconnection patterns such as El Niño-Southern Oscillation (ENSO) show that El Niño years are related to reduced precipitation, continental freshwater discharge, and evapotranspiration on land; therefore, TWS variability occurs over many land areas (Gonsamo et al., 2016). Many studies have attempted to address the possible causes of TWS changes by connecting TWS with TC (Phillips et al., 2012; Ndehedehe et al., 2017; Ni et al., 2018). However, these studies focused primarily on the effect of ENSO on TWS. Notably, many other global and regional climate TCs have also influenced the changes in TWS; these TCs, however, have been less extensively documented, which consequently limits our understanding of a comprehensive TWS-TC correlation. Therefore, knowledge of the influence of multiple TCs on TWS is critical for improving our understanding and proper management of water resources (Phillips et al., 2012; Ndehedehe et al., 2017).

In this study, we conducted a comprehensive analysis of the spatiotemporal variations in TWS across the Asian and Eastern European regions and address the contributions of each hydrological component and connection with TCs using multisource data. First, we calculated the de-seasonalized trend and analyzed the spatiotemporal variations in TWS across Asia and Eastern Europe. Then, we partitioned the components of TWS into SW, SM, and groundwater by using GRACE, a land surface model, and lakes and glacial observation data. Finally, we calculated the cross-correlation coefficients between TCs and the detrended and de-seasonalized TWS time series. We aimed to explore 1) the spatial pattern of long-term trends in TWS, 2) the contributions of water components to TWS variations among regions, and 3) the role of TCs in the changes in TWS and its components within the Asian and Eastern European regions.

2 Materials and Methods

2.1 Study area

The Asian and Eastern European regions, with arid and semiarid land comprising 54% of its total area, are located between latitudes 6°S and 56°N and longitudes 4°E and 109°E (Figure 1a). These regions are the most densely populated regions in the world, sustaining nearly half of the global population (Gridded Population of the World: GPW, v4), and contain some of the largest and most intensively irrigated lands of the world (Figure 1b). Freshwater availability in these water-limited regions is essential to food and water security and, hence, sustainable economics. However, the amount of available freshwater in these regions is highly dependent on precipitation and temperature (Wang, 2018); consequently, these factors are influenced intensively by the Northern Hemisphere atmospheric circulation patterns and the coupled ocean-atmosphere patterns (i.e., teleconnections). Therefore, spatially explicit analyses of the impacts of teleconnections on freshwater availability in these regions can provide a simple framework for understanding the complex response of freshwater availability to global climate change.

[Please Insert Figure 1 Here]

2.2 Data

GRACE satellite measures the vertical terrestrial water storage from the land surface to the deepest aquifers and can be used to monitor spatiotemporal variability in terrestrial water storage anomalies (Scanlon et al., 2016). The advanced mass concentration (mascon) approach contains a much higher signal-to-noise ratio in TWS retrieval than the traditional global spherical harmonics (SH) technique because of reduced leakage errors (Scanlon et al., 2018, 2019). Notably, the GRACE mascon solutions derived from the Jet Propulsion Laboratory (hereafter JPL-M) and the Center for Space Research (CSR-M) represent two fundamentally different approaches to applying constraints. The constraints applied in the JPL-M processing are based on both GRACE data and geophysical models for mass changes over land, oceans, ice, inland seas, earthquake areas, and areas affected by glacial isostatic adjustments (Watkins et al., 2015), whereas CSR-M constraints are based solely on GRACE data (Save et al., 2016). Meanwhile, the JPL-M solution has the unique characteristic that each 3°×3°

(approximately to the native resolution of GRACE data) mascon element is relatively uncorrelated with the neighboring mascon elements (Rodell, 2018). In this study, both the JPL-M and the CSR-M datasets were used to detect TWS changes across the Asian and Eastern European regions with spatial resolutions of 0.5° × 0.5° for the period between April 2002 and June 2017, for a total of 183 solutions. The missing data for the duration of 20 months in the original time series were filled by the linear interpolation method (Long et al., 2015; Yang et al., 2017). The GRACE anomalies reported in these mascon solutions are relative to a 2004–2009 mean baseline (Scanlon et al., 2016). For details on the data processing, please refer to Watkins et al. (2015) and for the mascon solutions, Save et al. (2016).

The Global Land Data Assimilation System (GLDAS) data between April 2002 and June 2017 was used to partition the GRACE-observed TWS changes into SW (snow water equivalent, canopy water, lakes and glaciers), SM and groundwater. The monthly data products from the GLDAS version 2.1 Noah model contain thirty-six parameters, including canopy water storage, snow water equivalent and SM data. Noah has a total of 4 layers of SM thickness: 0–10, 10–40, 40–100, and 100–200 cm. To compute the GLDAS TWS, the SM in all layers, the snow water equivalent, and canopy SW are summed. The summed GLDAS TWS is comparable to GRACE TWS over land (Rodell et al., 2004), and, notably, the GLDAS version used here does not include groundwater and separate SW components (such as rivers and lakes). Therefore, deviations from the GRACE total water storage changes can be expected. A comparison between GRACE and GLDAS is shown in Figure S1. The native spatial resolution of the GLDAS dataset is 0.25° × 0.25°; we resampled these data to a 0.5° × 0.5° spatial resolution using the nearest neighbor interpolation method prior to the analysis. The sea level (Caspian Sea, East Aral Sea, West Aral Sea, and North Aral Sea) data derived from multimission altimeter observations were obtained from the Database for Hydrological Time Series of Inland Water (Schwatke et al., 2015) and Hydroweb (Crétaux et al., 2011). Glacier mass change data (Tien Shan, Hindu Kush, Spiti Lahaul, East Nepal, Bhutan and Nyainqentanglha) are available from the published literature (Brun et al., 2017; Wang et al., 2018). The groundwater counterpart was estimated by deducting the estimated SW and SM changes from the GRACE-observed TWS change (Wang et al., 2018). Notably, interannual variations in biomass are considerably below the detection limits of GRACE (Rodell et al., 2005; Rodell et al., 2009); therefore, the variability in the SW counterpart mainly involves changes in lakes, snow, and ice in this study.

The term teleconnection may refer to patterns arising from the internal variability of the atmosphere as well as from the coupling between the air and the ocean (Zhu et al., 2017). In this study, we analyze the TCs that dominate climate variability in the Northern Hemisphere, including the Arctic Oscillation (AO), North Atlantic Oscillation (NAO), East Atlantic (EA), East Atlantic/Western Russia (EAWR), Scandinavia (SCAND), Polar/Eurasia (polarEA), West Pacific (WP), Pacific/North America (PNA); we also analyze four important atmosphere-ocean coupled variability patterns that influence global climate, including the Indian Ocean Dipole (IOD), the Atlantic Multidecadal Oscillation (AMO), the Pacific Decadal Oscillation (PDO), and ENSO (Zhu et al., 2017). The first 8 indices refer to Northern Hemisphere atmospheric circulation patterns. These 8 indices were calculated for 20°N–90°N using a rotated principal component analysis (RPCA) of monthly mean standardized 500-mb height anomalies (Barnston and Livezey, 1987). The IOD is defined by the difference in sea surface temperature between two areas – a western pole in the western Indian Ocean (50~ 70° E, 10° S~ 10° N) and an eastern pole in the eastern Indian Ocean (90~110° E, 10° S~ EQ). The IOD affects the climate of Asia and is an important contributor to rainfall variability in this region (Saji et al., 1999). The AMO and PDO indexes are defined as the leading principal component of the North Atlantic Ocean (0-65°N, 80°W-0°E) and the North Pacific Ocean (poleward to 20°N) monthly sea temperature variability, respectively (Enfield, 2001; Bond, 2000). ENSO is the most important coupled ocean-atmosphere phenomenon driving global climate variability. We adopted the monthly Multivariate ENSO Index (MEI) in this study, which considers the variability both in the atmosphere and in the ocean (Wolter and Timlin, 2011). All these indices were obtained from the Climate Prediction Center of the U.S. National Oceanic and Atmospheric Administration (Table 1).

[Please Insert Table 1 Here]

2.3 Methods

2.3.1 Time series decomposition

The original GRACE TWS signal is decomposed into long-term trends, seasonality signals, and residual components by implementing the Seasonal Decomposition of Time Series by Loess (STL) approach. The STL method is a robust method for time series decomposition, and the equation is as follows (Scanlon et al., 2016):

$$S_{total} = S_{long-term} + S_{seasonality} + Residuals\ , \qquad (1)$$

where S_{total} is the original signal, $S_{long-term}$ is the long-term trend, $S_{seasonality}$ is the seasonality signal and *Residual* is the residual component. An example is provided for a region in northwest India (Figure S2). For detailed principles and applications of STL, readers are encouraged to refer to (Cleveland et al., 1990; Bergmann et al., 2012).

2.3.2 Theil-Sen trend analysis

The de-seasonalized time series was used to calculate the linear trend of TWS and precipitation for the Asian and Eastern European regions from April 2002 to June 2017 using the Theil-Sen trend method. The advantage of the Theil-Sen trend analysis is that it is nonsensitive to outliers and therefore can be more accurate than a simple linear regression for skewed and heteroscedastic data (Sen, 1968). This method compares strongly against the least squares method, even for normally distributed data. The TWS trend, β, for a particular pixel is as follows:

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right), \forall\, j > i, \qquad (2)$$

where i and j are the time series sequences and x_i and x_j are the TWS values at times i and j, respectively. When β>0, the TWS in the corresponding pixel reveals an increasing trend; when β<0, the TWS in this pixel reveals a decreasing trend. The significance of the trend is tested by using the Mann-Kendall statistical test (Kendall, 1955).

2.3.3 Cross-correlation analysis

Contemporaneous weather conditions impact TWS residuals and often show evident time lags. Therefore, in this study, we employ the cross-correlation method to explore the relationship between the TWS residual and teleconnection indices. The cross-correlation measures the similarity of the two time series datasets as a function of the displacement of one set relative to the other (Oppenheim et al., 2009). The cross-correlation is defined as follows:

$$\rho(\tau)=\frac{\sigma_{12}(\tau)}{\sqrt{\sigma_{11}\sigma_{22}}}, \tag{3}$$

where σ_{12} (τ) is the cross-covariance function of x_{1} (t) leading the lagging x_{2} (t), and σ_{11} and σ_{22} represent the auto-variances of x_{1} (t) and x_{2} (t), respectively. The value of ρ (τ) lies between -1 and +1. Moreover, we focus on the current and historical influence of TCs on the TWS residual, and hence, we constrained the value of lag τ to range between 0 and 24 (Ni et al., 2018). Higher cross-correlation values indicate a stronger influence of a TC on a TWS residual and its components. In this study, we calculated the cross-correlation at the residual time series to partially remove the influence of unaccounted factors on TWS changes; this is because we assumed that the trend was mainly induced by secular climate change or direct human impacts rather than interannual climate variability (Phillips et al., 2012; Wang et al., 2018). The methodology flow diagram in Figure 2 shows the detailed process for data processing and analysis.

[Please Insert Figure 2 Here]

3 Results

3.1 Spatiotemporal changes in TWS

Both JPL-M and CSR-M show similar spatiotemporal pattern of changes in TWS (Figure 3 and Figure S3). Since the JPL-M solution has a lack of correlation between neighboring mascon elements in the retrieval, in this study we use JPL-M for trend analysis and mapping. JPL-M indicates that the Asian and Eastern European regions experienced widespread declines in TWS during 2002–2017 (Figure 3a). Noticeably, the spatial regime of the TWS variation matches that of the precipitation trend, except for northwest India, areas north and east of the Caspian Sea, and the area north of Xinjiang in China (Figure 3b), thereby suggesting that variations in TWS in these regions are intertwined with human impacts. The North China Plain (Region 1), a vast agricultural region in China, has undergone a continuously negative trend in TWS (-8.94±3.91 mm yr^{-1}), although an increasing trend in precipitation is expected in the northern part of this region (Figure 2b and Table S1). Another hotspot of TWS decline is located west of Urumqi in China's northwestern Xinjiang Province (Region 2), with a negative trend of -15.93±11.58 mm yr^{-1}. Rainfall in this region shows an increasing trend during the study period (Figure 2b). The most striking TWS deficit is in northwest India (Region 3), with a negative trend of -21.79±14.54 mm yr^{-1}. Two subcenters of TWS deficits (-11.74±8.11 mm yr^{-1}) are located in the border area of China, India, Bhutan, and Nepal (Region 4). The Middle East region witnessed the most widespread TWS depletion (-10.93±7.91 mm yr^{-1}) in the study area (Region 5), and the Caspian Sea level showed a dramatically negative trend (-73.2 mm yr^{-1}) during the GRACE era (Figure S4).

There are also several regions with increased TWS over the mid-high latitude, i.e., most regions of Russia and northeast China, coinciding with an increase in precipitation in these regions during the study period (Figure 3). Other hotspots with increased TWS in China during 2002–2017 are located in South China and the hinterlands of the Tibetan Plateau. In contrast to the sharp decline in TWS over northwest India, TWS in central and southern India exhibits an increasing trend during the GRACE era. The variability in southern monsoons and the associated increase in rainfall likely account for the positive trend in TWS (Rodell, 2018).

[Please Insert Figure 3 Here]

3.2 Influence of TC indices on TWS variability

Figure 4 shows the spatial distribution of the cross-correlation coefficients, illustrating the possible relationship of TCs with interannual variability in TWS. The results indicate that ENSO, AO, and NAO have a significant area of influence on TWS variability. Spatially, the pattern of correlation coefficients between TWS and ENSO is heterogeneous, with positive correlations occurring mostly in southeast China and boreal regions and negative correlations occurring in Southeast Asia, India, and eastern boreal regions. The second and third most dominant teleconnection modes are AO and NAO, respectively. AO mainly affects TWS variations across high-latitude regions through its impact on temperature variability, and NAO has a wider footprint that is scattered across the whole study area. Following the three dominant TCs, the positive effects of IOD are scattered throughout northwest India, southern Arabia, the European boreal region, northwest China, and the Yellow River basin, whereas the negative effects of IOD are mainly located in Southeast Asia. Other teleconnection modes typically have a smaller impact on TWS dynamics over the study area.

Proportions of time lags for different TCs are shown in Figure 4d. Nearly half of the area (49.14%) lags behind the TCs by up to 3 months, while the proportions of TWS variations lagging behind the TCs at 4–6 months and at 7–9 months are 20.27% and 12.28%, respectively. These time lags are mainly scattered in the mid-high-latitude region and the Yangtze River basin in China. Longer lags (10-18 months), accounting for 18.31%, are observed in parts of the Tibetan plateau, the Mongolia plateau, and the Middle East region. Notably, the spatial pattern of the dominant TC has only a limited extent with respect to their influence on climate conditions. The heterogeneous pattern highlighted the importance of focusing on the effect of multiple TCs on TWS rather than one teleconnection index.

[Please Insert Figure 4 Here]

3.3 Contributions of water storage components to TWS

The changes in TWS aggregate the contributions of different water storage components (Figure 5). Groundwater depletion (-8.68±2.89 mm yr^{-1}) dominates the contribution to TWS loss in region 1 compared to the other two components (-0.27±2.97 mm yr^{-1} for SM, 0.02±0.11 mm yr^{-1} for SW) during the study period. Similar results were observed in northwest India (region 3 with -21.35 mm yr^{-1}), which contained the most extensive land irrigation area worldwide (Figure 1b). The contributions of the SW and soil water in the above two regions are extremely small and neglected. The rapid glacial mass loss in the Tien Shan Mountain range induced a 41% water loss (Jacob et al., 2012; Brun et al., 2017). The melt water and the increase in precipitation replenished the soil water, leading to an increase in soil water components (2.18±2.82 mm yr^{-1}) in northwest China (region 2). Notably, groundwater in region 2 contributed to more than half (-11.61±13.02 mm yr^{-1}) of the total water loss. In this region, both groundwater depletion and glacial melt may enhance evapotranspiration by pumping water from aquifers and mountains to the surface, contributing to a negative trend in TWS. The contributions of region 4 are 2.48±1.81 mm yr^{-1}, -3.22±7.24 mm yr^{-1} and -11.00±10.43 mm yr^{-1} for SW, SM, and groundwater, respectively, suggesting that groundwater withdrawal is the primary reason for TWS depletion. This region is also spatially coherent with precipitation deficits, as depicted in Figure 2b; this dynamic is especially prominent in the eastern part of this hotspot, thus accentuating the loss of TWS. The prominent SW loss (-3.83±1.68 mm yr^{-1}) in region 5 can be attributed to the prominent shrinkage in the Caspian Sea as demonstrated by a decrease in its water level elevation by -73.2 mm yr^{-1}, which is similar to the sea's -68 mm yr^{-1} decline during 2002–2016 (Wang et al., 2018). The dramatic decline in the Caspian Sea level contributes to a third of the total TWS loss in this region. The large decrease in TWS in these areas can also be attributed to the heavy reliance on groundwater for irrigation and domestic needs due to the construction of dams upstream (Voss et al., 2013; Rodell et al., 2018). The slight decreasing trend in precipitation likely exacerbated the TWS depletion, as the change of TWS relied largely on precipitation in those water-limited regions. Our results suggest that TWS variations during 2002–2017 had different impacts on SW (lakes, biomass, snow, and ice), SM, and groundwater among the five hotspot regions.

[Please Insert Figure 5 Here]

3.4 Divergent response of water storage components to TCs

Our results indicate that the water storage components are simultaneously influenced by several teleconnections (Table S2). For instance, SM in region 2 significantly correlates with NAO, AO, EAWR, PNA, ENSO, IOD, EA, AMO, polarEA and PDO, with negative correlations for some indices and positive correlations with others. Moreover, the dominant teleconnection varies for different water storage components among the separate regions (Table S3). The changes in TWS and groundwater are generally less sensitive to TC signals compared to the surface and SM counterparts. A possible explanation may be that TWS is a synthesis signal, i.e., its trend will be offset by its components in different ways. The groundwater component intensively interferes with anthropogenic activities such as irrigation and domestic needs and groundwater withdrawal, which indicates a lower correlation with TCs.

Further seasonal analysis indicates that the response of water storage to TCs is seasonally different from one region to another (Figure 6). For example, TC signals have a dominant control on TWS and component variability in spring and summer for region 3 and region 1, respectively, whereas the signals control most of the changes in SM in region 5 in autumn and winter. Notably, although it has been thoroughly documented that the dramatic decline in TWS in northwest India can be attributed to the overexploitation of groundwater (Rodell et al., 2009), our seasonal response of water components to TCs suggests that the SM in this region is highly correlated with spring ENSO signals (Figure 4, r = 0.77). These results highlight the importance of understanding the seasonal responses to TCs to improve predictions of changes in TWS and associated water storage components.

[Please Insert Figure 6 Here]

4 Discussion

4.1 Comparison of TWS trends to existing studies

We investigated the spatiotemporal trend of TWS and its components over Asia and Eastern Europe during 2002–2017. The spatial patterns and trends of TWS throughout the study area are consistent with those of previous studies (Humphrey et al., 2016; Scanlon et al., 2016). Our estimated trend (-8.94±3.91 mm yr^{-1}) of TWS in region 1 is similar to the results of previous studies in this region (22±3 mm yr^{-1} during 2003-2010) (Feng et al., 2013; Tangdamrongsub et al., 2018). The discrepancies may stem from the inconsistency of the study period and spatial domain. Due to a warm and dry long-term climate and intensive anthropogenic activities (agriculture, industry, and urbanization), the groundwater in region 1 has been overexploited since the 1970s, and more than 70% of the groundwater exploitation is used for regional irrigation (Wang et al., 2007). The groundwater loss rate in region 3 (-21.35 mm yr^{-1}) was also comparable with a previous study in region 3, with approximately 40±10 mm yr^{-1} from August 2002 to October 2008 (Rodell et al., 2009). As Indian agriculture leads the world in total irrigated land by consuming ~85% of the utilizable water resources (Salmon et al., 2015; Panda et al., 2016), a consensus has been reached that the dramatic decline in TWS is mainly due to the overexploitation (extraction exceeding recharge) of groundwater for irrigation (Shamsudduha et al., 2019). Although precipitation in region 3 shows an increasing trend during the GRACE period, the rapid depletion of TWS in northwest India induced by unsustainable consumption of groundwater for irrigation and other anthropogenic uses has attracted worldwide attention because it is a major threat to India's sustainability (Rodell et al., 2009; Panda et al., 2016). Region 4 in our study is heavily irrigated (Figure 1); hence, intensive irrigation is likely to induce groundwater decline (-11.00±10.43 mm yr^{-1}). The increase in SW induced by melt water from mountains (Brun et al., 2017) was offset by the decrease in soil water, which may have been related to the decrease in precipitation (Figure 3b). For region 2, the rapid melting of the glaciers of Tien Shan Mountain accelerated the losses of water resources, as the glacial meltwater will provide additional water that was lost to rivers or evaporation (Jacob et al., 2012). The negative trend in TWS indicates that water demand is larger than the supply in region 2, which can be attributed to both a continuous withdrawal of groundwater and extensive evaporation in the endorheic basin (Rodell et al., 2018). However, the increase in precipitation is expected to offset a certain portion of water losses in region 2. Previous studies also documented that the widespread decline in TWS in region 5 is attributed to an overreliance on groundwater for domestic and agricultural needs stemming from human-made dams in addition to the considerable surface water loss (Voss et al., 2013; Joodaki et al., 2014; Rodell et al., 2018). These existing analyses indicate that the widespread declines in TWS values and their hydrological components are primarily attributed to the intensive over-extraction of groundwater or warm-induced surface water loss, which are consistent with the findings in this study.

4.2 Possible mechanisms of TC influence on TWS variability

Periodic variability in the climate system can strongly influence regional meteorological patterns and their associated TWS. Unlike a single meteorological variable, teleconnection patterns control heat, moisture, and momentum balances through their effects on temperature, precipitation, and solar radiation reaching the Earth's surface (Zhu et al., 2017; Ni et al., 2018). Therefore, the inherent mechanisms of the TCs' influence on TWS variations are related to the combined simultaneous effects of TCs on regional climate factors (precipitation, temperature, and radiation); the changes in climate factors will substantially affect the recharge (precipitation) and loss (evapotranspiration) of regional water resources, which eventually influence the changes in TWS. We have identified several dominant TCs that influence the variability in TWS and its components. Spatially, ENSO mainly controls the TWS variation over Southeast Asia, Southeast China, and India. During positive ENSO phases, warmer and drier conditions can easily occur over these regions. Higher temperatures and lower precipitation are both associated with an eventual decrease in TWS in these areas (Ni et al., 2017). IOD is similar to ENSO and often co-occurs with ENSO (Du et al., 2009). During a positive IOD phase, anomalous cool (warm) waters appear in the eastern (western) Indian Ocean in association with large-scale circulation changes that bring anomalous dry conditions to Southeast Asia, i.e., Indonesia, while East Africa experiences above-average rainfall (Webster et al., 1999). The IOD may exert a negative impact on TWS due to the decrease of precipitation over Southeast Asia. Similarly, AO primarily dominates TWS variations in high-latitude areas and the surroundings of the Black Sea regions. When the AO index is positive, and the vortex is intense, the winds tighten like a noose around the North Pole, locking cold air in place and contributing to unusual warmth over the Northern Hemisphere land masses (Zhou et al., 2001). This unusual warmth could lead to an increase in water loss through the evapotranspiration process, thereby contributing to a negative impact on TWS. The positive phase of the NAO, which is highly correlated with AO ($r = 0.64$, $p < 0.01$), leads to an intensification of the west wind drift due to a reinforcement of the Iceland low and the Azores high pressure systems; this phenomenon is particularly apparent in the boreal winter months (Wallace et al., 1981). In turn, these results show positive precipitation anomalies in central Europe and negative anomalies in southern Europe and on the Norwegian coast, which is reflected in the water storage variations. Other TCs explain relatively small fractions of atmospheric variability in a given region by primarily interfering with hydrothermal processes. These results imply that climate variability may exert important influences on the TWS. Although previous studies mainly focused on the influence of ENSO on TWS (Phillips et al., 2012; Zhang et al., 2015; Ni et al., 2018), a single indicator is unlikely to represent all climatic variability features over a large area (Zhu et al., 2017). In this study, we provide a comprehensive analysis of twelve commonly used teleconnection indices; these results indicate that the dominant TCs vary considerably for each component and region. Therefore, attributions and predictions of the changes of TWS and its components based on a single TC should be approached with caution, and multiple TCs are strongly recommended to explain the changes in TWS and its components.

4.3 Uncertainties and implications for future hydrological studies

Our results indicate that climate variability could explain the variability in TWS in most remote and sparsely populated regions. To a certain extent, climate variability may also indirectly explain glacial melt-induced changes in TWS, such as warming-induced glacial retreat. However, climate variability is influenced by human activities, such as groundwater abstraction in regions with intensive human activities. Although we obtained the contributions of different water storage components (SW, SM, and groundwater) through TWS partitioning, each component also influenced both the climate variability and human activities, which makes determinations of the influences of climate change and other processes extremely complicated. Thus, well-designed experiments and coupled human-natural system models are still needed to clarify the quantitative contributions of each influencing factor on TWS and its components' variability (Rakovec et al., 2016; Zhang et al., 2017). Several uncertainties also exist in understanding the changes in TWS and its components over the Asian and Eastern European regions. These may include the unaccounted reservoirs and rivers in surface water storage, which may induce uncertainties in a certain area in groundwater estimation by eliminating the surface water and soil moisture from TWS. The glacier data used in this study was obtained during 2000–2016, which was inconsistent with our study period (2002–2017); this incongruity may also have caused uncertainties in separating the water components from TWS. Nevertheless, our study provides a new view of teleconnections that can enable a more thorough understanding of the changes in TWS. Moreover, our study focused primarily on a water storage deficit hotspot analysis because a basin-based evaluation may experience bias in calculating the basin-averaged TWS when a given basin simultaneously experiences drying and wetting trends in different sub-basins (Sun et al., 2018). A multiscale hydrological model with high spatial and temporal resolutions may help in understanding the effects of climate variability on the hydrological response across the globe (Samaniego et al., 2010; Rakovec et al., 2019). We infer that climate variability-induced extremes, such as drought and heatwaves, will exacerbate the TWS loss; this occurs through increased consumption of water resources from groundwater for irrigation and human water demand in these hotspots, rather than the climate variability alone being the sole cause for the observed TWS loss.

There are several recommendations for future hydrological studies: 1) withdrawal of freshwater from groundwater in water-limited regions is important for the sustainable development of water resources and food supplies (Rodell et al., 2018). However, groundwater drought is a distinct phenomenon resulting from a decrease in groundwater storage (Thomas et al., 2017). Understanding groundwater drought is important in water-limited regions where the interplay between groundwater recharge and abstraction results in variable groundwater stress conditions. GRACE has the unique potential to obtain data on groundwater storage by introducing subsidiary datasets. 2) Glacier mass loss in mountainous areas can relieve drought stress in drought years (Huss et al., 2018), but it can additionally result in hydroclimatic extremes, e.g., floods. Neither of these phenomena can be detected using only precipitation datasets, such as those commonly used in monitoring drought and flood events (Sherwood et al., 2014); this highlights the importance of TWS-related hydroclimatic extremes. With the release of the GRACE follow-up satellite (Famiglietti et al., 2013), consecutive prolonged data records could provide a valuable solution for evaluating hydrological conditions from a long-term perspective and would lead to considerable improvements in our knowledge of TWS-related hydroclimatic extremes (Famiglietti et al., 2013). 3) A recent study found that the CO_2 growth rate is strongly sensitive to observed changes in TWS (Humphrey et al., 2018), and the coupling between the water and carbon cycles highlights the need for stronger interactions between the hydrological and biogeochemical research communities to achieve a sustainable development of the Earth system.

5 Conclusions

In this study, we characterize the spatiotemporal variations in TWS as well as its components and connect these variations with TCs over the Asian and Eastern European regions from April 2002 to June 2017 using multiple data sources. The results indicate a widespread decline in TWS during 2002–2017, and five hotspots of TWS negative trends were identified with trends ranging between -8.94 mm yr^{-1} and -21.79 mm yr^{-1}. Partitioning of TWS suggests that these negative trends are mainly attributed to intensive groundwater extraction and warming-induced SW loss, but the contributions of each hydrological component vary from region to region. The results also indicate that ENSO, AO, and NAO are the three dominant factors in controlling variations in TWS through their covariability effects on climate variables. However, seasonal results suggest a divergent response of hydrological components to TCs among seasons and regions. This highlights the importance of knowledge of the seasonal responses to TCs to improve the understanding and prediction of changes in TWS and associated water storage components. Our study provides a comprehensive analysis of TWS variability and its connection to TCs across the Asian and Eastern European regions, thus facilitating the target strategy of water resource management.

Data availability

The data and code generated in this study are available from the authors upon request (liuxianfeng7987@163.com).

Author contributions

XL and XF conceived and designed the research, XL conducted the experiments and analysed the results, XL wrote the manuscript with contributions from XF, CP and BF.

Competing interests

The authors declare that they have no conflict of interest.

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Figures:

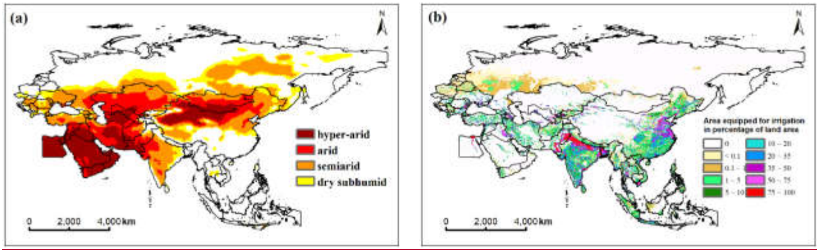

Figure 1: Boundaries of the Asian and Eastern European regions. Panel (a) is the spatial distribution of arid and semiarid areas based on the averaged aridity index during 2002–2017. The aridity index is calculated based on the ERA-Interim dataset downloaded from European Centre for Medium-Range Weather Forecasts. Panel (b) is the percentage area of irrigated land across the study area. The percentage area of irrigated land dataset is derived from Food and Agriculture Organization of the United Nations.

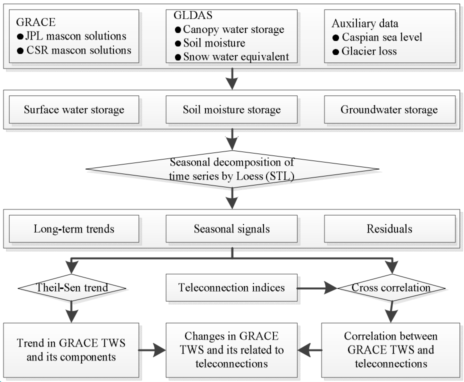

Figure 2: Methodology flow diagram of data processing in this study.

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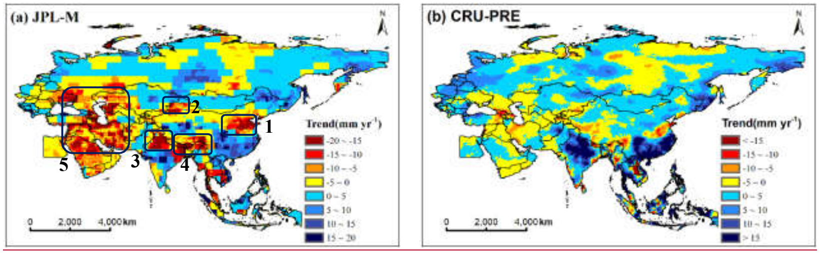

Figure 3: Spatiotemporal changes in TWS as obtained from GRACE (a) and precipitation as obtained from CRU (b) across the Asian and Eastern European regions during 2002–2017. The trend is obtained from the removed seasonal cycle time series.

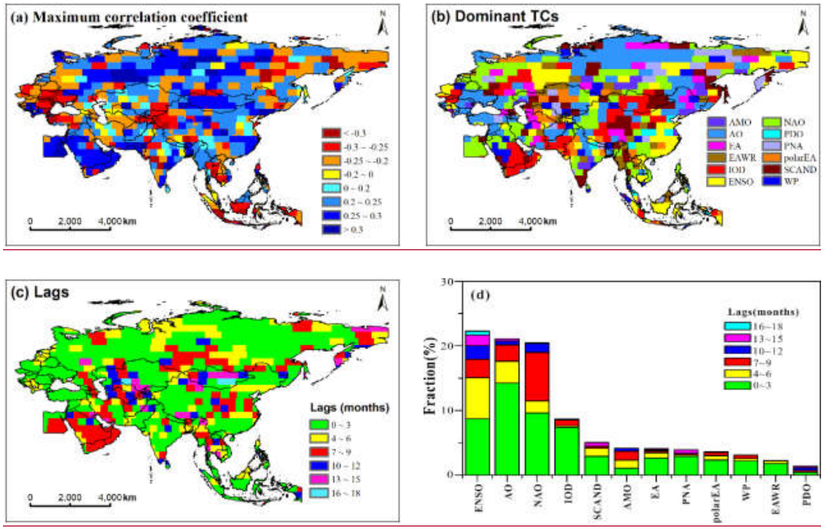

Figure 4: Spatial distribution of cross correlation analysis between TWS and teleconnection indices. (a) Spatial pattern of maximum correlation coefficients between TWS and the teleconnection indices. (b) Spatial pattern of teleconnections that can most accurately represent TWS variations. (c) Spatial pattern of teleconnection lag time. (d) Proportion of the area dominated by each teleconnection and its corresponding time lags. The maximum lag in the correlation analysis was limited to 0–24 months (significance threshold: |r| > ~0.15 given a significance level = 0.05 and a time series number = 183).

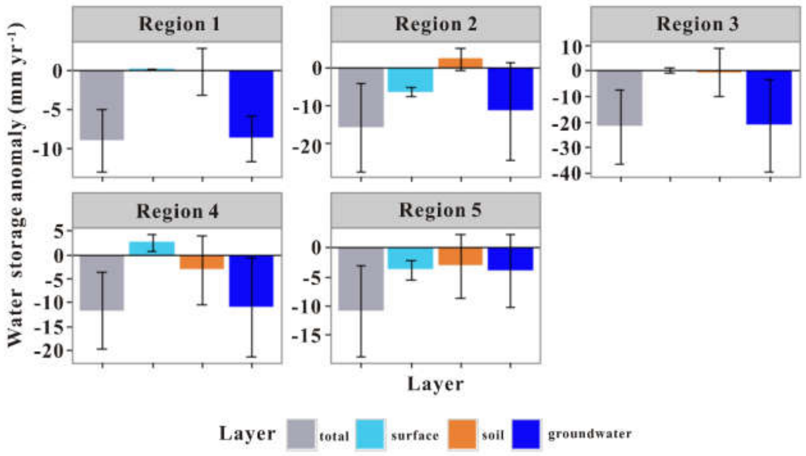

Figure 5: Contributions of different hydrological storages to TWS changes in five hotspots. Uncertainties represent 95% confidence intervals.

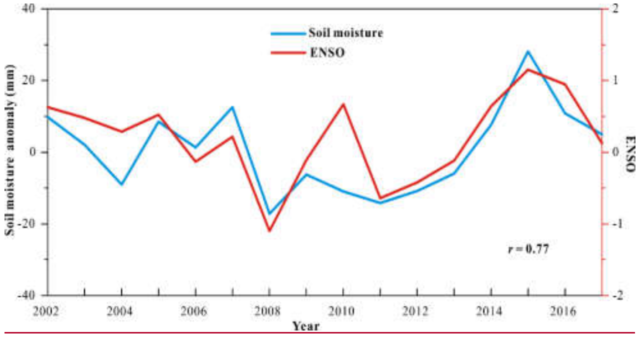

Figure 6: The residual time series of spring soil moisture and associated ENSO in region 3 during 2002–2017.

Table 1: Descriptions of datasets used in this study

Datasets	Variables	Time span	Resolution	Source
GRACE	JPL-M	2002-2017	monthly and 0.5°	The Jet Propulsion Laboratory (Watkins et al., 2015) and the Center for Space Research (Save et al., 2016)
	CSR-M			
GLDAS	Canopy	2002-2017	monthly and 0.25°	The Global Land Data Assimilation System data (Rodell et al., 2004)
	Soil moisture			
	Snow water			
Lakes	Caspian sea	2002-2017	ten days and site	The Database for Hydrological Time Series of Inland Water (Schwatke et al., 2015) and Hydroweb (Crétaux et al., 2011)
	Aral Sea (East)			
	Aral Sea (West)			
	Aral Sea (North)			
Glacier	Tien Shan	2000-2016	year and regional	Literature (Brun et al., 2017)
	Hindu Kush			
	Spiti Lahaul			
	East Nepal			
	Bhutan			
	Nyainqentanglha			
Teleconnections	AO, NAO, EA, EAWR, WP, polarEA, PNA, IOD, AMO, PDO, ENSO, SCAND	2002-2017	monthly and global	The Climate Prediction Center of the U.S. National Oceanic and Atmospheric Administration