We thank the two anonymous reviewers for the constructive comments and appreciate their expertise. Here are the point-to-point responses to their comments.

Reviewer #1

The paper of Zhang et al investigates quantifies the trends in rainfall decrease in Southwest China and investigates whether and how atmospheric circulation plays a role. The paper is easy to read and the figures generally support the text and vice versa. The study is novel in the sense that atmospheric tracking has not often been applied to trends in precipitation, but rather for climatologies or variability studies only.

A: Thanks for the comments. We truly appreciate it.

That being said, I have a few concerns with the manuscript, which I hope the authors can address in a revised version:

1. Units are not used consistently up to (what should be) the scientific standard. Precipitation should always be per a unit of time, thus mm mon^{-1} and never just mm. Trends should always be per unit of time squared, thus mm yr^{-2} or mm mon^{-1} $decade^{-1}$ and never just mm yr^{-1}. Same holds for moisture flux divergence (or in fact any flux). The sister journal of ACP, HESS, has a good guide: http://www.hydrology-and-earth-system-sciences.net/for_authors/manuscript_preparation.html under mathematical requirements.

A: Units have been changed to fit the standard of ACP in the revision. The trends are expressed as per unit of time squared. The fluxes including precipitation and moisture divergence are all expressed as per unit of time throughout the paper.

2. The water accounting model (WAM) has received several updates since van der Ent et al. (2010), and it is not clear whether the authors use the updated version with two vertical layers (van der Ent et al., 2014), which is apparently open source now (van der Ent, 2016). This may be very relevant due to the wind shear present in the area under investigation, which will lead to biases when vertically integrated fluxes are

being used (van der Ent et al., 2013; Goessling and Reick, 2013).

A: The original version of WAM (WAM1), instead of the two vertical layer model (WAM2), was applied in this study. To address the concern on model versions, we tested the potential contribution of wind shear to moisture flux by calculating the moisture flux shear factor following Eqs. (7-8) in van der Ent et al. (2013) in the target area (see Fig. 8 in revision). Lower value indicates stronger moisture flux shear. The areal-weighted shear factor at the zonal direction over summer (JAS) in study area SWC during 1979-2013 is 0.72, while it is 0.76 at the meridional direction. Taking the zonal shear factor as an example, a shear factor of 0.72 means that 86% of the water goes in one direction with 14% in the opposite direction. Because the dominant moisture flux has a high share of the overall flux, the moisture flux shear is not strong in this case.

To further confirm that, we selected the year 1986 with the strongest moisture flux shear (The averaged zonal and meridional shear factor in summer 1986 is 0.71) as a sample case and applied the WAM2 for comparison. The results (Fig. 9) show that the spatial patterns of moisture contribution match with each other between WAM1 and WAM2. This is not the case as in van der Ent et al. (2013), where WAM2 shew distinct spatial pattern with WAM1. Thus, WAM1 is considered suitable for this study. We have added the results of moisture flux shear and the comparison of two WAM versions into the 4.1 section of sensitivity analysis on WAM.

3. There is limited background information on the ground-based precipitation dataset from CMA. It is always tricky to do trend analysis on interpolated data for which the stations on which the dataset is based might not be homogeneous. I suggest the authors give more information on the number of stations used, whether that is constant, are there data gaps, is it just stations or satellite information as well? And a reason why they think it is safe to apply trend analysis on this dataset.

A: The CMA (China Meteorological Administration) precipitation dataset is based on ground observations of ~2400 stations over China (Shen and Xiong, 2016). The stations within this study area are shown in revised Fig. 1b. The data are quality *controlled and released by CMA. It is seen as one of the best ground-based precipitation products over China and it is widely used in many studies. In the revision, a brief discussion on the CMA dataset is provided (P3, L5-7).*

4. The decomposition of moisture transport is not well enough explained. The results seem relevant, but from the information in the paper I do not see how this could be easily reproduced.

A: Section "2.3 Decomposing moisture transport" has been revised by adding formulas to explain the decomposition of moisture transport. We have added short subparagraphs to detail the analysis method (P4, L25-28 and P5, L4-7). The decomposition process was described in detail in the references Li et al. (2013) and Seager et al. (2010). As it is a widely used procedure in the research field, it should not be difficult to reproduce following the guidance in the references.

5. P1, L19: "at a rate of -23.6 mm^{-1} decade" This is just one of the many examples what I mean with the wrong use of units. Because the unit is incorrect it leaves the reader wondering whether this is -23.6 mm per year per decade or -23.6 mm per decade per decade or -23.6 mm per month per decade or -23.6 mm per day per decade. Admittedly, these mistakes can be found abundantly in the scientific literature, but it is no excuse, in my opinion, to take such issues lightly, rather I hope that the authors agree with me and start correcting themselves as well as others.

A: We agree with the reviewer on the unit issue. The units have been carefully checked and corrected in the revision.

6. P2, L27-28: "The ERA-I data have a spatial resolution of 1.5° × 1.5° grid cell" Apparently this is the resolution that the authors used (which is ok), but other (higher) resolution are also available, thus please rephrase this sentence.

A: There are ERA-I data with other resolutions, and the 1.5 degree data were used in this study. The sentence has been rephrased in P2,L32-P3,L1.

7. P2, L30-P3, L2: Here, the authors explain that they have replaced the evaporation and precipitation fields from ERA-I with CMA precipitation and GLDAS evaporation, because of existing "limitations in the reanalysis estimates". The claim about limitations is, however, not being backed up with a reference or figures and nor is any proof given that the alternative datasets are any better. I suggest the authors to back up this choice of data better.

A: It is well-known that the reanalysis data such as ERA-I have large biases on precipitation estimates, and so as the evaporation estimates (Trenberth et al., 2011; Tong et al., 2013). The CMA precipitation data is from ground-based observations and was released by CMA, the Administration which is responsible for meteorological observations in China (http://www.cma.gov.cn/en2014/). The GLDAS is forced with precipitation gauge observations among others (Rodell et al., 2004). Both datasets are observation-based and are better than the estimates in the reanalysis data. In the revision, we have provided the related references to back up the choice of data (P3, L3-4, L6-7, L9, respectively).

8. P3, L5: "backward in time" As far as I know backward tracking with WAM has been applied by Keys et al. (2012) for the first time.

A: We have corrected the citation and have added Keys et al. (2012) at P3, L18 in the revision.

9. P3-P4: "Section 2.3 Decomposing moisture transport" This entire section could benefit from equations and figures to explain the concept behind decomposition.

A: This section has been revised by adding formulas to explain the decomposition method.

10. P4, L21-22: "As shown in Fig. 2, the farther away from the target region, the lower intensity of moisture is contributed to the target (Zhang C. et al., 2017)"

I think it is a bit misplaced to cite just an own paper here as there are literally dozens of other papers that used back-trajectory methods which have found this. Moreover, it is not even as simple as put here, because it naturally depends on the winds (otherwise we could just draws circles around the target region)

A: Thanks for your suggestions. More references have been added in the revision (P6, L2). In addition, the statement has been modified to reflect the key message, that is, the moisture contribution differing in different directions depends on the winds (P6, L2-4). As shown in the Fig. 3a, for the study area, more moisture is from the south and less moisture from the north.

11. P4-P5, "Section 3.1 Moisture origin" I think previous literature is not sufficiently cited in relation to the findings of this paper. A few papers that have source region figures for China or sub-regions of China that for example could be of interest (Keys et al., 2014; Wei et al., 2012, 2016).

A: We have cited some references and compared the findings with the previous references in this study (P6, L5-6; L23-27). The comparisons are generally consistent, although the focus areas are not the same. We have also emphasized that we focus more on the changes of the moisture contribution, rather than the climatological pattern in this study (P1, L26-28).

12. P7, L5: "the Asian monsoon regions" Which are exactly? Would it perhaps make sense to delineate them somewhere?

A: "The Asian monsoon regions" here means from the northern Indian Ocean to SWC and from South China Sea to SWC. We have modified the statement and specified the exact regions in the revision (P10, L19-20).

13. P7: "Data availability" What about the data availability of the CMA product? This section should be expanded according to the ACP guidelines: http://www.atmospheric-chemistry-and-physics.net/about/data_policy.html

A: The CMA product was released by CMA and was downloaded from the China Meteorological Data Service Center (CMDC, http://data.cma.cn/en, http://data.cma.cn/data/cdcdetail/dataCode/SURF_CLI_CHN_PRE_DAY_GRID_0.5.

html). The site has been provided in the Data availability section in the revision.

14. The summer months appear to be July, August and September, whereas the meteorological summer for the northern hemisphere is generally regarded as June, July, August. Why the difference? The fact that JAS is considered should be 100% clear in all figure and table captions.

A: We focused on July, August and September because precipitation in these months shows large and significant trends over the study area. We agree that meteorological summer usually indicates June, July, and August. In the revision, we have limited the use of summer, instead we use July, August and September (JAS) throughout the manuscript.

15. Figure 2: the caption should include what the contribution to total precipitation the red boundary in Fig. 2a encompasses. I saw it mentioned in the text, but not in the figure caption itself.

A: The caption has been revised to include the information (Figure 3; P18, L3-4).

16. Figure 2: why is the Tibetan Plateau relevant?

A: The Tibetan Plateau situates in the upwind of SWC. Due to its high altitude, it is well-known that it will block the moisture from the west to SWC (Tian et al., 2007; Yu et al., 2008). It can be seen from Figure 3a that little moisture contribution from the west of the Tibetan Plateau. However, the Tibetan Plateau itself may contribute moisture to SWC (Huang and Cui, 2015), which is also seen from Figure 3a. Thus, it explains the moisture contribution pattern (relative high contribution from eastern Tibetan Plateau, but close to zero contribution from the western and west to the Tibetan Plateau). It is an important finding regarding how the high altitude of the Tibetan Plateau affects moisture contribution pattern. These reasons have been clarified in the revision (P6, L19-24).

17. Figure 2: There are multiple black lines (also the target region), which makes the

caption confusing.

A: The line colors have been adjusted. The target region is changed to brown. The land outline is changed to gray. The division line between East and West is black. And the figure is also changed to Figure 3.

18. Fig. 2b: The information between 0 and 1 and -1 and 0 seems quite relevant, could the authors add more colors?

A: The color bar has been modified following the suggestion (see Fig. 3b).

19. Figure 2: Is the boundary between East and West expert judgement? The art of the modeler? Or is there some physical determining factor?

A: The boundary is based on the result (Fig. 3b) following the distinct opposite sign of the moisture trend. In the west side, the moisture contribution is decreasing while it is increasing in the east side. It has been clarified in the text (P6, L11-12).

20. Figure S1: What do the colors mean? The color scale lacks units or explanation in the caption.

A: The colors represent the moisture divergence of the fluxes. The units have been added in the caption on the next page (P2, L2-4).

21. TECHNICAL CORRECTIONS

As mentioned before, units should be corrected throughout the paper.

A: The units have been corrected throughout the revised paper.

References

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Reviewer #2

The authors present a climatological study of moisture transport to a region in China, analysing trends in precipitation from Reanalysis and gridded station data. Trends in moisture origin and moisture convergence are also analysed. The paper is generally well-written and the methods are mostly sound. However, there are several uncertainties in this analysis that need further discussion, and some statements need additional justification. I suggest to include another section providing a discussion of the method uncertainties and the possible impact on the results. Furthermore, I could imagine that the manuscript may possibly find more readership in a specific climate journal, maybe the Handling Co-Editor has some thoughts on this. Below I detail my major and specific comments.

A: We appreciate the insightful and constructive suggestions. We have added another section to provide discussion of model uncertainties and carefully justified the related statements. The paper is not only about the climatology of moisture transport, but also the dynamic causes of changes in moisture transport. We think it is certainly within the scope of ACP. The point-to-point responses to the comments are listed below.

1. The method description should be improved by explicitly naming some of the underlying assumptions. For example, the calculation of a proportion of precipitation relative to total column water implies that water vapour is well-mixed at every grid cell. Do the results depend on grid spacing of the input data? A figure would help to support the explanation of how the WAM method works.

A: 1) Although the full description of WAM should refer to the listed founding works (van der Ent et al., 2010; van der Ent and Savenije, 2011; Keys et al., 2012), the WAM method has been better described in the revision including discussion on the well-mixed assumptions (P3,L32-P4,L4 and P8,L27-P9,L2).

2) Given the size of the study area, we believe the chosen resolution of the input data is appropriate. Our choice is also motivated by previous studies which successfully applied the same 1.5° ERA-I data (e.g., van der Ent and Savenije, 2011; van der Ent *et al., 2010; Keys et al., 2012; 2014; Zhang et al., 2017).*

2. The authors state in Sec. 2.2 that after 30 days, "a large amount of water may be left in the air" and that they continue for another 30 days. Please quantify how large an amount is left in the atmosphere after 30 days. What is the origin of this uncertainty? How realistic is it to assume precipitation water stays in the atmosphere for 60 days (2 months) in this region?

A: 1) The precipitation moisture is tracked monthly. Take July for example, we would track the moisture from 7.31 to 7.1. In fact, precipitation may occur at the beginning of the month on 7.1. If we stopped tracking at 7.1, the precipitation moisture would be left in the air and not have been allocated to its surface sources. Many studies show that the average residence time of water vapor in the atmosphere is around 10 days (Trenberth, 1998; Numaguti, 1999; Trenberth, 1999). But this measurement of residence time is e-folding based, which means that after 10 days, there is still 1/e (i.e., 36.8%) of the original water vapor left in the air. In order to track more precipitation moisture, we prolong the track process to more than 10 days, as in our case 30 days, to guarantee that most (>95%) of the monthly precipitation can be tracked. This is a Eulerian way of tracking moisture too. It is different from the Lagrangian method that usually tracks the precipitation events backward for around 10 days. The 10 days limit is also due to the accuracy of the trajectories (Stohl, 1998).

2) Take July as an example, the tracked moisture accounts for 65.1% of precipitation on average from 1979-2013 when the tracked time is from 7.31 to 7.1, while it accounts for 97.4% when tracked from 7.31 to 6.1.

3. The method uses a combination of reanalysis and observational data that are blended together and partly rescaled. Could it be that inconsistencies between the ERA-Interim water cycle and observations bias the results, and impact the trend analysis? What are the uncertainties of this combination of data used? How do uncertainties in P and E parameterisations influence the results? This should be discussed and evaluated in more detail, maybe in a separate "method

sensitivity/method discussion" section.

A: We use observation-based P and E estimates to rescale the P and E in the ERA-I data because ERA-I estimates have large biases (Trenberth et al., 2011). The blend of P and E does not affect the direction of moisture fluxes in the ERA-I data, rather it affects the magnitude of the contribution. We have conducted the experiments for comparison with E and P from ERA-I (in section 4.2 of revision). The results are shown in Fig. 10. The essential pattern of moisture contribution is similar, except that the sources tend to contribute more with ERA-I E and P, since the SWC precipitation in JAS is higher with ERA-I than with CMA (see Fig. 2b). The major region (enclosed by the 0.27 mm mon^{-1} red line in Fig. 3a) contributing 88.3% of precipitation with CMA, contributes 89.4% with ERA-I. The trend patterns are generally the same with both datasets as more moisture comes from the East and less from the West (Fig. 10b). The major results are thus unaffected. We have added a section (section 4.2) to evaluate the possible uncertainty caused by the change of P and E.

4. The display of moisture contributions in Fig. 2 is cut off at 0.8 mm, providing 88.3% of the total precipitation. Is there a justification for choosing this percentile? It would be helpful to add also the contours encompassing 50% and 95% of the total precipitation in the figure.

A: If 100% is set, the moisture contribution area will cover the whole globe. If a small portion, such as 50% is set, the moisture contribution area will be a small area around the study area. We certainly do not want to include the whole globe because the contribution become very small if the contributing area is far away from the study area. We do not want to set a small number because only a small portion of moisture contribution was accounted for. Thus there is a trade-off because the contributing area and the portion of the moisture contribution. If we select 95%, it will cover most of the globe with many areas with contribution close to 0. Thus we set a number close to 90% which cover most area with relative large contribution. We have provided a 50% region in the revision (Fig. 3a) but we did not analyze the data based on the region because it can only represent half of the moisture contribution to the study area.

5. The trend obtained in the analyses seem to depend strongly on the years 2006 and 2011. Is there a significant trend observed if these two years were removed from the time series? How reliable are trends from reanalysis data in general?

A: 1) The declining trend is also significant at 5% level when the two years are removed. The CMA precipitation product is based on ground observations and is quality controlled by CMA. The drying trends and drought in southwest China were reported by many previous studies using independent datasets (e.g., Tan et al., 2016; Barriopedro et al., 2012; Li et al., 2011). Thus, the trend of CMA data is taken as reliable.

2) In general, the precipitation trend in the reanalysis data is not very reliable since precipitation in reanalysis is model output which is not directly constrained by observations (Dee et al., 2011; Berrisford et al., 2011). In Fig. 2, we have plotted the precipitation data from ERA-I together with the ground observation. It is evident that ERA-I estimates have large biases which are much larger than those of CMA. However, the trends are all significant at 5% level and show similar decreasing patterns and magnitudes for both annual mean and summer (JAS) precipitations.

6. Some conclusions seem not sufficiently based on evidence in the manuscript. This includes the statement that "local recycling played a minor role" (pg. 5, L. 12), that the "dominant role of dynamic process ... prevails over a very large area" (pg. 6, L. 20), and the speculation of a possible role of SST anomalies in the changes (pg. 6, L. 30). Notably, the "might be related" in that line becomes a "likely related" in the conclusions (pg. 7, L. 16), even though no evidence to that end is presented in the manuscript. A clearer and more balanced argumentation, including alternative interpretations, should be formulated in all of these cases. The statement "the westerlies play a secondary role" (pg. 7, L. 5) has also no clear anchoring in the results presented before.

A: We have carefully checked these statements, and kept only those with sound evidences in the revision. We have paid attention to the consistency of the statement in *the results section and conclusion section.*

7. More references to the literature on the topic of moisture source analyses should be included in the introduction and in the discussion of the uncertainties of the results. In addition to the studies by Gustafsson and Zhang, consider some of the earlier founding work from Stohl and James (2004,2005), James et al. (2004), Sodemann et al. (2008), Sodemann and Zubler (2010), Baker et al. (2015), Winschall et al. (2014). Also relevant are the discussion of the uncertainties of the well-mixed assumption (Goessling and Reick, 2013).

A: We have added more references in the results and discussion section to discuss the uncertainties of the results (P6, L4-6; L23-27), in the introduction and methodology sections (P2, L24 and P3, L18-20) to compare different methods, and in the 4.1 section on WAM to discuss the uncertainties of the well-mixed assumption.

8. Pg. 1, L. 14: "monsoon region" please specify which monsoon region

A: It is the Asian monsoon regions, which in this paper specifically mean regions from the northern Indian Ocean to SWC and from South China Sea to SWC. We have specified the exact regions in the revision (P1, L14-15).

9). Pg. 2, L. 4: descend flows -> descending motion

A: Corrected (P2, L6).

10. Pg. 2, L. 21: seems somewhat circular, please rephrase. Analysing the moisture sources and transport appears to me as another way of looking at circulation patterns, but with a focus on one aspect of precipitation (the other one being lifing/condensation).

A: We intended to say 'providing insights on how the changes in atmospheric circulation may affect precipitation in SWC'. We have rephrased the statement (P2, L23-26).

11. Pg. 2, L. 27: Unclear how the Trenberth (1991) citation fits in here.

A: It has been deleted (P2, L32).

12. Pg. 2, L. 28: grid cell -> degree

A: Corrected as in P3, L1.

13. Pg. 3, L. 8: Is this vertially integrated moisture transport?

A: Yes. We've also clarified it in the text (P3, L22-23).

14. Pg. 3, L. 25: Please clarify how exactly the rescaling was done in order to ensure reproducibility of your results. What rescaling factor was used?

A: At each grid, there is a CMA value and an ERA-I value for the monthly precipitation. The monthly CMA value is taken as the norm, thus producing a rescaling factor ε for the ERA-I value. Then, all the precipitation values (3 h) during a month of ERA-I are rescaled using the factor ε. But the ε varies with grids and months. We have clarified it in the revised paper (P4, L13-15).

15. Pg. 4, L. 5: At what level where q and wind velocity considered for this analysis?

A: All the levels are vertically integrated.

16. Pg. 4, L. 10: has experienced -> shows

A: Changed (P5, L13).

17. Pg. 4, L. 22-23: lapses -> decreases

A: Changed (P6, L3).

18. Pg. 4, L. 24: delete "precipitation"

A: Deleted (P6, L4).

19. Pg. 4, L. 24: the finding that humid regions provide more moisture than arid regions is quite obvious; the description could provide more quantitative detail

A: We intend to say that water surface tend to provide more moisture compared with the neighboring dry land surface under similar conditions, which can be easily told from the shading gradient in Fig. 3a. It's of little importance in the aim of this study. We have rephrased the sentence in the text (P6, L9-10).

20. Pg. 5, L. 8: Figure 2 has already been introduced above

A: It has been combined with the above description (P6, L28-29).

21. Pg. 5, L. 15: please define what you mean by "moisture supply"

A: It has been defined in the revision (P6, L29).

22. Pg. 5, L. 15-25: How dependent are these results on the threshold of 0.8mm? In general, I find the moisture flux change vectors difficult to relate to the moisture contribution change, because the moisture flux is calculated for the entire atmospheric humidity, and not for the contribution to the target region.

A: The result is independent from the threshold of 0.8mm (0.27 as in unit mm mon^{-1}). The threshold of 0.8mm is use to delineate the key area which contributing moisture to the study area. Figure 4 shows the moisture contribution change in last and first 10-year time period.

We agree that moisture flux change vectors do not have to be related to the moisture contribution change. Figure 4 shows mainly the moisture contribution changes. The moisture flux change vectors were overlapped to provide clues on changes of moisture contribution. As more moisture is transported toward the target area, more moisture may contribute to precipitation in the study area. The relation between moisture divergence and precipitation in the study area is further investigated in Figure 5 and 6.

23. Pg. 5, L. 30: how was moisture divergence calculated?

A: The field of moisture divergence is calculated directly from the field of moisture flux. We have clarified it at P5, L4.

24. Pg. 5, L. 32: "the close correlation": is that the only possible conclusion? My understanding is that moisture divergence is related to precipitation by mass balance requirements, but does not provide insight into the roles of moisture transport vs. local evaporation. Please elaborate.

A: At a time scale longer than one month, the moisture balance equation of P = E-div(Q) holds. So P is not only related to moisture divergence, but also E. However, the correlation coefficients between P and E are -0.18, 0.39, and 0.23 for July, August, and September, respectively, lower than those of P and moisture divergence (-0.87, -0.88, and -0.74). This makes moisture transport a more influential factor to P changes. We have added the analysis of the P, E, and moisture flux divergence change in the revision (P7, L18-21). Our finding is also consistent with that in Li et al. (2013). Li et al. (2013) performed a similar analysis in southwest China which is closely the same area as in this study.

25. Pg. 6, L. 12: Obvious is a quite subjective term. Are the trends significant? How reliable are such trends from reanalysis data?

A: 1) The dynamic component of moisture transport shows an increasing trend significant at 5% level and we have changed "obvious" to "significant" in the text (P8, L4-5).

2) The reanalysis parameters differ according to whether they are produced by the analysis or the forecast. The analysis fields are constrained by the observations while the forecast are produced by the model (Berrisford et al., 2011; Dee et al., 2011). The moisture transport is derived from humidity and wind variables from the analysis fields. Though there are uncertainties, these observation-constrained fields are more reliable than those from model forecast such as precipitation, evaporation, etc. (Berrisford et al., 2011). In addition, ERA-I, as a modern reanalysis, has significantly improved in comparison to the older ERA-40 *(https://climatedataguide.ucar.edu/climate-data/era-interim; Trenberth et al., 2011). The interannual variation in moisture transport with ERA-I is rather stable (Trenberth et al., 2011) which gives us more confidence in its application. Nonetheless, current reanalysis provide the best reconstruction of atmosphere records for the climate change research in the atmosphere field. In the revision, we have stated that the results are derived from the reanalysis data and provided a brief discussion on the data reliability of the reanalysis data (P9, L20-27).*

26. Pg. 6, L. 20: Data availability for the CMA data should be stated.

A: It has been stated in the revision (P11, L7-8).

27. Figure 1a: Please provide a wider area in the figure panel, including some topography contours and maybe country names for orientation. A distinction between the national boundaries and province boundaries would also be helpful.

A: We have polished the figure in the revision (Fig. 1a).

28. Figure 2a: Does the green shading indicate that all areas shown in the figure panel contribute >0 mm to the target area?

A: Yes (Fig. 3a in revision).

29. Figure 3: Is it possible to restrict the shading and moisture flux vectors to moisture arriving in the target region only?

A: The shading is already restricted to moisture reaching the target region. For the moisture flux, however, it is impossible within the WAM framework to restrict it to the moisture reaching the target region yet.

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Tracing changes in atmospheric moisture supply to the drying Southwest China

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Abstract. Precipitation over Southwest China (SWC) has significantly decreased during 1979–2013. The ~~summer~~ months from July to September (JAS) contributed the most to the decrease of precipitation. By tracing moisture sources of ~~summer~~ JAS precipitation over the SWC region, it is found that most moisture originates in ~~the monsoon~~ regions from the northern Indian Ocean to SWC and from South China Sea to SWC. The major moisture contributing area is divided into an extended west region, SWC, and an extended east region. The extended west region is mainly influenced by the South Asian Summer Monsoon (SASM) and the westerlies, while the extended east region is mainly influenced by the East Asian Summer Monsoon (EASM). The extended west, SWC, and extended east regions contribute 48.2%, 15.5%, and 24.5% of the moisture for the SWC precipitation, respectively. Moisture supply from the extended west region decreased at a rate of -~~23.6~~7.9 mm mon^{-1} decade^{-1} whereas that from the extended east increased at a rate of ~~4.2~~1.4 mm mon^{-1} decade^{-1}, resulting in an overall decrease of moisture supply. Further analysis reveals that the decline of ~~summer~~ JAS precipitation is mainly caused by change in the seasonal-mean ~~stationary~~ component rather than the transient component of the moisture transport over the SWC region. In addition, t~~T~~he dynamic processes (i.e.~~,~~ changes in ~~circulation~~wind) rather than the thermodynamic processes (i.e., changes in specific humidity) ~~is~~ are dominant in affecting the seasonal-mean ~~stationary~~ moisture transport. A prevailing easterly anomaly of moisture transport that weakened moisture supply from the Indian Ocean is to a large extent responsible for the precipitation decrease over the SWC region.

1 Introduction

Frequent and severe droughts hit Southwest China (SWC) over the last decades with record-breaking events in the summer of 2006 and 2011, which had caused great losses to the society. The intensified drought is characterized by the persistent deficit of precipitation (Wang et al., 2015b), and has attracted much attention (e.g. Barriopedro et al., 2012; Feng et al., 2014; Wang et al., 2015b; Tan et al., 2016; He et al., 2016; Zhang X. et al., 2017).

Many studies have analyzed the meteorological conditions that caused the extremely low precipitation for individual drought cases (e.g. Li et al., 2011; Lu et al., 2011; Yang et al., 2012). Taking the drought of summer 2006 as an example, a stronger Western Pacific Subtropical High (WPSH) was found to lie anomalously northward and westward (Li et al., 2011). Under the direct control of WPSH, ~~descent~~ descending ~~flows~~ motion prevailed over SWC and the moisture transport from the Bay of Bengal (BOB) and South China Sea (SCS) was suppressed (Liu et al., 2009; Li et al., 2011). Further analysis revealed that the active convection over the Philippines and the weaker-than-normal heat source of the Tibetan Plateau drove the strengthened WPSH to shift northward and westward (Li et al., 2011). Meanwhile, a weak blocking high in the Ural Mountains and a shallow East Asian trough facilitated a stronger-than-normal zonal circulation in the mid-latitudes, which hindered the intrusion of cold air into SWC (Zou and Gao, 2007). In summary, the configuration of the large-scale subtropical and mid-latitude circulations was unfavorable for the warm-moist air from the south and cold-dry air from the north to converge over SWC, and thus produced the severe drought.

Some recent studies have endeavored to investigate the mechanisms causing the SWC drying ~~in~~ from a long climatological perspective. Using stalagmite record as a proxy, Tan et al. (2016) found the period of 2009-2012 was the driest ever since 1760 AD in SWC. They further attributed the drying trend to the warming of Tropical Ocean, which had reduced the land-sea thermal gradient and the amount of moisture transported from the BOB. In another study, the possible influence of sea surface temperature (SST) in tropical Northwest Pacific (NWP) on the autumn precipitation in SWC was investigated (Wang et al., 2015a). It was found that the warm SST in NWP had likely contributed to the dry condition in SWC in recent decades.

Although previous studies have deepened our understanding of the SWC drying through attributing individual/general drought events or long-term precipitation trend to some probable causes, few of them have analyzed the changes in the precipitation moisture sources of this region. Tracing ~~the precipitation~~ moisture sources not only can reveal the origin of moisture for precipitation (Gustafsson et al., 2010; Zhang C. et al., 2017; James et al., 2004; Sodemann and Zubler, 2010), ~~thus providing~~ it can also provide insight~~s~~ ~~on~~ to ~~how the~~ long term changes in moisture ~~sources~~ as well as how atmospheric circulations ~~may~~ affect precipitation in SWC. This study intends to identify changes in moisture sources of the SWC precipitation and study the relative changes in moisture transport during the last several decades ~~and~~ to investigate the possible mechanism of the SWC drying.

2 Data, study area, and Methodology

2.1 Data and study area

The reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim (ERA-I hereafter) was used to calculate precipitable water and moisture flux (Dee et al., 2011~~; Trenberth, 1991~~). The ERA-I data adopted in this study

~~have a spatial resolution~~ are ~~of~~on a grid of 1.5° × 1.5° ~~grid cell~~, and the time ~~span of the ERA-I in this study~~ is from 1979 to 2013. The data include the 6-h wind and moisture content at multiple levels from 200–1000 hPa, and surface pressure.

Due to the existing limitation with precipitation ~~and evaporation~~ estimates in reanalysis products (Trenberth et al., 2011; Tong et al., 2014), the ground-based 0.5°-gridded daily precipitation dataset from the China Meteorological Administration (CMA) was used (Zhao et al., 2014; Zhao and Zhu, 2015). The CMA dataset is based on surface observations of ~2400 stations over China (Fig 1a). The gauge data are quality controlled but not homogenized. According to an estimation by Shen and Xiong (2015), the inhomogeneous stations takes up about 1.46% of all the stations. The 3-h 1°-gridded evaporation fields from the Community Land Model in the Global Land Data Assimilation Systems (GLDAS, Rodell et al., 2004) dataset were ~~used~~chosen as GLDAS outperforms other reanalysis on surface variables (Wang and Zeng, 2012; Gao et al., 2014). Over the ocean, the evaporation fields in ERA-I reanalysis were used directly, since there is no alternative estimate.

The study area of SWC mainly encompasses three provinces of Sichuan, Yunnan, and Guizhou, and one municipality of Chongqing (Fig. 1a).It sits in the southeast foot of the Tibetan Plateau. In north SWC, the eastern Sichuan and Chongqing form the Sichuan Basin, while in south SWC, Yunnan and Guizhou form the Yun-Gui Plateau with an average altitude of around 2 km. The topographic height data are provided by the Global Land One-km Base Elevation Project (GLOBE).

2.2 Water Accounting Model

The Water Accounting Model (WAM) is an Eulerian model on moisture recycling, which can quantify the moisture source-sink relations between evaporation and precipitation by tracking moisture forward or backward in time (van der Ent et al., 2010; van der Ent and Savenije, 2011; Keys et al., 2012). It is quite different from those Lagrangian models such as FLEXPART and HYSPLIT which track moisture based on the particle trajectories (Stohl and James, 2004; 2005; Sodemann et al., 2008; Draxler and Hess, 1998). In this study, moisture backtracking of WAM was applied to track the moisture origins of and their changes with the SWC precipitation. The algorithm is briefly described as follows.

The input of WAM includes precipitation, evaporation, and atmospheric data (precipitable water and the vertically integrated moisture transport). The fallen precipitation in the target area was assumed to return to the air as "tagged water" in the model. The tagged water was mixed into the precipitable water with a ratio of r, which means only r proportion of the precipitable water would finally fall into the target area. When it reverses the way back along the transport path, a certain amount of moisture, which is evaporated from the sources in the path, would fall into the target area. The ratio of that certain amount is also r. Taking the first source grid for example, it evaporates an amount of e into the air at this time step. At the same time, the mixed ratio is r, and then the only $e*r$ would finally fall into the target area. The direct contribution from the grid at this time step is $e*r$. The tagged water would reduce the same amount of $e*r$ and move on to the next source grids till all the tagged water is depleted. By then, the total moisture contribution from each grid can be summed to produce a spatial distribution of moisture contributed to the precipitation in the target area.

As seen from the algorithm, the WAM is a 2-D model with the "well-mixed" assumption, where the tagged water mixes into the precipitable water sufficiently and the mixed ratio is independent of height. Though the well-mixed moisture conditions are not always met, a relatively low degree of vertical mixing suffices to maintain close to well-mixed conditions for the case of moisture flux with vertically uniform wind directions (Goessling and Reick, 2013). For the case of strong directional shear of the horizontal moisture flux, a two-vertical-layer version of WAM was introduced by van der Ent et al. (2013) that solved the vertical inhomogeneities satisfyingly. The two-layer WAM is also implemented in the sensitivity analysis section as a validation to the one-layer WAM results.

The time step of WAM was set to 0.5 h for 1.5° grid in this study as in van der Ent et al. (2010) and van der Ent and Savenije (2011). The 6-h atmospheric data of precipitable water and moisture flux were linearly interpolated into the 0.5-h time step. For evaporation, the 1°-gridded GLDAS data were first interpolated into the 1.5° grid over the land, and then were merged with the ocean evaporation from the ERA-I reanalysis. The merged evaporation, which was 3-h accumulated, was divided equally into the 0.5-h time step. For precipitation, in order to reflect the diurnal cycle, the daily CMA and 3-h ERA-I precipitation fields were merged. The CMA precipitation was firstly transformed to the same spatial resolution as ERA-I by taking the means of the 0.5° grids that fell into the 1.5° grid. Then both monthly CMA and ERA-I precipitations were calculated for each 1.5° grid. ~~-~~By taking the monthly CMA value as norm, a rescaling factor ε was produced for the monthly ERA-I value for each grid. All the ERA-I precipitation values (3 h) during a month within the grid were rescaled using the factor ε. ~~By setting the monthly CMA precipitation as a norm, all ERA-I precipitation during a month was rescaled proportionally.~~ Finally, the rescaled 3-h-accumulated ERA-I precipitation was equally distributed over the 0.5-h time step.

When the WAM was applied at a monthly scale, a large amount of tagged water may be left in the air after one month's tracking rather than allocated to the surface sources. In this case, the backtracking would continue to run another 30 days with no input of precipitation to ensure that 95% of the monthly precipitation moisture returned to the surface.

2.3 Decomposing moisture transport

To further understand the change of moisture transport in association with the change of moisture origin, the monthly vertically integrated moisture flux was decomposed into a stationary component and a transient component (Eq. (1); Li L. et al., 2013~~a~~).

$$\overline{\mathbf{Q}} = \underbrace{\frac{1}{g}\int_{P_t}^{P_s} \overline{q}\,\overline{\mathbf{V}}\,dp}_{\text{Stationary}} + \underbrace{\frac{1}{g}\int_{P_t}^{P_s} \overline{q'\mathbf{V}'}\,dp}_{\text{Transient}}, \qquad (1)$$

where Q is the vertically integrated moisture flux, g is the acceleration of gravity, q is the specific humidity, V is the horizontal wind vector, P_s is the surface pressure, P_t is the pressure at the top of the troposphere. The bars denote the monthly mean of variables, which is calculated using the average of 6-hourly values in each month. The apostrophes denote the anomalies of 6-hourly values to their monthly mean. The stationary component is the monthly mean moisture transported by the monthly mean ~~flow~~wind, while the transient component is the transient moisture transported by the transient eddies. ~~The stationary component was calculated using the average of 6-h values in each month. The transient component was calculated using the 6-h deviations from the monthly mean.~~

The fluctuation of the stationary component in expression of divergence can be further ~~expressed by~~decomposed into ~~a~~ thermodynamic and ~~a~~ dynamic terms (Eq. (2); Seager et al., 2010; Li L. et al., 2013~~a~~).

$$\delta\left(\int_{P_t}^{P_s}\nabla\cdot\left(\overline{q}\overline{\mathbf{V}}\right)dp\right)\approx\underbrace{\int_{P_t}^{P_s}\nabla\cdot\left(\overline{q}_a\overline{\mathbf{V}}_c\right)dp}_{\text{Thermodynamic}}+\underbrace{\int_{P_t}^{P_s}\nabla\cdot\left(\overline{q}_c\overline{\mathbf{V}}_a\right)dp}_{\text{Dynamic}},\qquad(2)$$

where $\nabla\cdot$ is the divergence operator and the divergence is calculated directly from the field of moisture flux; δ denotes the fluctuation of the stationary component to its climatology; the subscript "c" denotes climatology and "a" the interannual deviation from the climatology; $\overline{q}_c$ and $\overline{\mathbf{V}}_c$ are the 35-year climatology of monthly mean specific humidity and wind velocity, respectively; $\overline{q}_a$ and $\overline{\mathbf{V}}_a$ are the deviations from the 35-year climatology of each month. The thermodynamic (dynamic) component ~~was~~ is solely determined by the changes in specific humidity (wind velocity) and thus represents the thermodynamic (dynamic) contribution (Li L. et al., 2013~~a~~). ~~The variations in stationary and transient components and thermodynamic and dynamic terms were analyzed.~~

3 Results and discussion

Figure ~~1a~~ 1b shows the annual precipitation trends from 1979–2013 calculated from the CMA gridded precipitation over the SWC region as marked out by the red box. The SWC precipitation ~~has experienced~~shows a declining trend in recent decades. The area-averaged annual SWC precipitation has decreased significantly with a rate of -2.72 mm yr^{-2}~~^{1}~~ (Fig. ~~1b~~2a). Table 1 provides the monthly precipitation trends during 1979–2013. It shows that the monthly trends from March to May are positive, although they are not statistically significant. The decreasing trends are the largest in the summer months of July, August, and September (JAS) with rates of -0.5, -1.1, and -1.0 mm month^{-1} yr^{-1} ~~in July, August, and September~~, respectively. The decreasing trend is statistically significant at the 6% (1%) level in August (September). The total ~~summer~~ JAS precipitation decreased significantly at the 5% level with a rate of -~~2.57~~0.86 mm mon^{-1} yr^{-1} (Fig. ~~1c~~2b). The precipitation series with ERA-I over SWC are also shown in Fig. 2. It is evident that ERA-I estimates have large biases which are much larger than those with CMA, especially at annual scale. However, the two series both show similar decreasing patterns and comparable trend magnitudes with the CMA precipitations.~~, which accounts for 94.5% of the annual trend.~~ ~~Since~~ As the ~~summer~~ JAS precipitation ~~change~~ trend accounts for a major share of the annual precipitation trend (94.5% with CMA data), the analysis below will focus on the ~~summer~~ JAS months.

3.1 Moisture origin and the trend in moisture contribution

The climatological moisture contributions from the source grids in ~~summer~~ JAS and their trends during 1979–2013 are shown in Fig. ~~2~~3. The major moisture contributing region, i.e., grids with contribution over 0.~~8~~27 mm mon^{-1} ~~yr^{-1}~~, are marked out (Fig. ~~2a~~3a), where 88.3% of ~~summer~~ JAS precipitation moisture in SWC comes from. ~~As shown in Fig.~~

~~2~~Generally, the farther away from the target region, the lower intensity of moisture is contributed to the target (Zhang C. et al., 2017; Keys et al., 2012; 2014). Yet, the lapse rate of moisture contribution intensity differs in different directions. ~~The moisture contribution intensity~~It decreases ~~lapses~~ slowly to the southwest and southeast, where moisture is transported by the Asian monsoons, indicating that the monsoon regions provide considerable amount of ~~precipitation~~ moisture to SWC. This result is consistent with Drumond et al. (2011), who traced precipitation moisture in Yunnan province from April to September and found two strong moisture sources of the Arabian Sea and the BOB, respectively. In contrast, the intensity ~~lapses~~ decreases rapidly to the north, suggesting that little ~~precipitation~~ moisture originates from the north. To the west of the SWC region, the intensity of moisture contribution is low in ~~the~~ dry lands ~~area~~ such as the Middle East but is relatively high in ~~surrounding~~ wet areas such as the Caspian Sea and the Red Sea, suggesting that ~~humid region~~these water bodies tend to provide~~s~~ more moisture than ~~arid~~ the neighbouring dry ~~region~~lands.

As the moisture contribution trends show an ~~opposing~~ opposite pattern in the west and east (Fig. ~~2b~~3b), the major moisture contributing region is divided into three regions, namely the extended west, SWC, and the extended east regions. The extended west region covers an area west and southwest to SWC, and the extended east region covers an area east to SWC and a part of the Indian Ocean. Figure S1 shows the climatological moisture transport from July to September. It indicates moisture from the extended west region largely enters the western and southern borders of SWC whereas moisture from the extended east region enters the eastern border via a route through ~~the~~ SCS. Moisture from the extended west region is likely affected by the South Asian Summer Monsoon (SASM) and the westerlies, while that from the extended east region is likely affected by the East Asian Summer Monsoon (EASM). When summed over regions, the extended west, SWC, and the extended east regions contribute 48.2%, 15.5%, and 24.5% of the total precipitation moisture, respectively. As SWC situates eastward and downwind of the Tibetan Plateau (Fig. S1), moisture from regions to the west of the Plateau is mainly blocked by the Plateau, while the Plateau itself serves as a more important moisture source. According to statistics, ~~The moisture contribution directly from~~ the Tibetan Plateau ~~i~~contributes ~~only~~ around 11.5% of the SWC precipitation, ~~much~~ less than that from the SASM and EASM regions ~~(Yao et al., 2012; Huang and Cui, 2015)~~. Huang and Cui (2015) also notified the important role of Tibetan Plateau as a major source to provide moisture for precipitation in the Sichuan Basin. As the Basin situates in north SWC, south SWC is, however, more accessible to the monsoons (Drumond et al., 2011). Thus, it is reasonable that the monsoons, which bring abundant moisture, contribute primary moisture to the JAS precipitation in SWC, while the westerlies contribute secondarily.

~~Figure 2b shows the trend of moisture contributed to the SWC summer precipitation from different regions during 1979–2013.~~ Moisture supply (i.e., moisture contributed to the SWC precipitation) from most of the extended west region experienced a decreasing trend of -~~23.6~~7.9 mm mon^{-1} decade^{-1}, accounting for 91.7% of the SWC precipitation trend, while that from most of the extended east region experienced an increasing trend of ~~4.2~~1.4 mm mon^{-1} decade^{-1} (Fig. 3b). The trend of local moisture ~~contributed~~ contribution ~~from~~ to SWC precipitation is -~~1.2~~0.4 mm mon^{-1} decade^{-1}, accounting for 4.6% of the SWC precipitation trend,~~.~~ ~~It~~which suggests that change in local recycling played a minor role in the precipitation decrease over SWC.

Figure ~~3~~ 4 shows the changes in moisture contribution and moisture transport in July, August, and September between the first and last ten years of the period of 1979–2013. Overall, there is an apparent decline of moisture supply from the west and southwest regions to SWC in all the three months. The area with the largest decline of moisture contribution includes the Indian subcontinent and Indochina over the land and the BOB over the sea. Compared with the moisture transport in the first ten years, more moisture from the Indian Ocean has been routed to the northern Indian subcontinent or the Tibetan Plateau, rather than into SWC in the last ten years. Consequently, moisture contribution influenced by the SASM is ~~weakening~~weakened. In contrast, moisture contribution has increased in many parts of the extended east region. In July, the area with increased moisture contribution includes the northern Central Indian Ocean, SCS, and a northeastern area of SWC. It looks like that more moisture from the northern Central Indian Ocean has been routed to SWC via SCS in the last decade of 1979–2013. In August and September, the main area with increased moisture contribution is located to the east and south of SWC, while a part of the northern Central Indian Ocean also contributed more moisture to SWC compared to the first ten years. The prevailing easterly moisture transport in ~~the~~ recent decade in South China support an enhanced contribution of the SWC precipitation moisture from the EASM region. The southern part of SWC that is largely affected by the SASM and westerlies experienced a decrease of moisture contribution.

3.2 Thermodynamic and dynamic control of moisture transport

The role of moisture transport is further investigated by analyzing the relations between moisture divergence and precipitation over SWC during 1979–2013. Correlation coefficients between moisture divergence and precipitation over SWC are calculated, which turn out as -0.87, -0.88, and -0.74 for July, August, and September, respectively. As evaporation is another component that forms the long-term moisture balance equation of $P = E - \mathrm{div}(Q)$, the correlation coefficients between P and E are also calculated, which turn out to be -0.18, 0.39, and 0.23 for July, August, and September, respectively. The much closer correlations between moisture divergence and precipitation indicate~~s~~ that remote moisture transport is more important than local surface evaporation in regulating the interannual variation of ~~summer~~ JAS precipitation (Li X. et al., 2013~~b~~).

Figure ~~4~~ 5 shows the 35-year climatology and time series of moisture divergence over SWC and their stationary and transient parts. The moisture divergences over SWC are negative as expected (see also Fig. S1). The stationary component of moisture divergence is also negative. The transient component is, however, positive. It indicates the transient eddies counteract the mean flow in moisture flux convergence/divergence~~s moisture into~~ in SWC~~, while the transient eddies diverge moisture~~. The magnitude of the transient component is about 30% of that of the stationary component, further suggesting that the change in the stationary component plays a major role in changing the moisture divergence over SWC (Fig. ~~4a~~5a). During 1979–2013, the stationary component increased, and the transient component decreased, resulting in an increasing trend of the moisture divergence (Fig. ~~4b~~5b). It suggests that the change in the mean flow rather than the transient eddies has led to the decrease of ~~SWC summer~~ JAS precipitation in SWC.

Figure ~~5~~ 6 shows the changes in thermodynamic and dynamic components of the stationary moisture transport in ~~summer~~ JAS over SWC during 1979–2013. The variation of the thermodynamic component is small compared with that of the dynamic component, suggesting that the dynamic processes, i.e., changes in atmospheric circulation (wind), exerted a dominant influence on the variation of moisture transport. The dynamic component shows an ~~obvious~~ increasing trend significant at 5% level during 1979-2013, while the thermodynamic component shows a small negative trend. The increase of moisture divergence, i.e., decrease of moisture convergence, by the dynamic component is in line with the decreasing precipitation (Table 1). The correlation coefficients between the dynamic component of moisture transport and precipitation over SWC are calculated. According to the calculated coefficients of determination~~Based on the correlation coefficients~~, the dynamic component explains 80%, 81%, and 58% of the precipitation variances for July, August, and September, respectively. It confirms the dominant role of the dynamic processes in regulating the precipitation change in SWC. Indeed, ~~T~~the interannual variation in the SASM net precipitation (within the Arbian Sea-the Indian Subcontinent-BOB) is also dominated by the dynamic process (Walker et al., 2015). ~~This~~ It suggests that the dominant role played by ~~of~~ the dynamic processes in regulating moisture transport and regional precipitation, not only validates in SWC, but prevails over a ~~very~~ quite large area.

Figure ~~6~~ 7 compares the dynamic component in ~~summer (July, August, and September)~~JAS between the first and last ten years of the period of 1979–2013. There is an overall positive anomaly of moisture divergence over SWC with an easterly anomaly of moisture transport. Though there is a southwesterly anomaly of moisture transport from the Indian Ocean to the SWC direction in July and September, it does not contribute moisture transport to SWC because the anomaly ends on the south of the Tibetan Plateau. There is an easterly anomaly along the southern edge of the Tibetan Plateau, routing the moisture transport to the northern Indian subcontinent instead of the SWC region. The anomaly of moisture divergence, dynamically caused by the changes in circulation, is generally negative in the Indian subcontinent but positive in SWC (Tan et al., 2016). The prevailing easterly anomaly of moisture transport and pronounced regional anomalies of moisture divergence over SWC are likely to result from the change in the Asian summer monsoon system (Wei et al., 2014), which might be related to recent Pacific cooling and Indian Ocean warming (Ueda et al., 2015).

4 Sensitivity analysis

4.1 On WAM

In the study, the one vertical layer version of WAM (WAM1) was applied. WAM1 uses the vertically integrated fluxes with the moisture being well-mixed within the atmospheric column. As a matter of fact, “well-mixed” conditions of tagged atmospheric moisture are usually not met (Bosilovich, 2002; Goessling and Reick, 2013). At the same time if the horizontal winds are sheared vertically in direction, vertical inhomogeneities will generate, which may lead to substantial errors with 2-D moisture tracking models (Goessling and Reick, 2013). van der Ent et al. (2013) advanced WAM1 to the two vertical layer

WAM (WAM2) that satisfyingly solved this problem and gave a simple metric to assess wind shear on when to use which model. The equations on the horizontal moisture flux shear following van der Ent et al. (2013) are

$$F_z = \frac{\left|\int_{P_t}^{P_s} qudp\right|}{\int_{P_t}^{P_s} |qu|dp} \quad (3)$$

and

$$F_m = \frac{\left|\int_{P_t}^{P_s} qvdp\right|}{\int_{P_t}^{P_s} |qv|dp}, \quad (4)$$

where F_z and F_m represent the zonal and meridional moisture flux shear, respectively. It can be easily judged that the flux shear value falls on a range between 0 and 1. The lower the value, the stronger the moisture flux shear. The climate means of horizontal moisture flux shear factors in JAS from 1979-2013 are shown in Fig. 8. The areal-weighted shear factor at the zonal direction over JAS SWC during 1979-2013 is 0.72, while it is 0.76 at the meridional direction. Taking the zonal shear factor as an example, a shear factor of 0.72 means that 86% of the water goes in one direction with 14% in the opposite direction. Because the dominant moisture flux has a high share of the overall flux, the moisture flux shear is rather small in this case.

To further verify the applicability of WAM1, the year 1986 with the strongest moisture flux shear (the averaged zonal and meridional shear factor in JAS 1986 is 0.71) was selected to perform an inter-model comparison between WAM1 and WAM2. As the atmospheric input data for WAM2 are model-level based, additional suite of ERA-I model-level atmospheric data in 1986 was prepared. The moisture contribution for JAS precipitation in 1986 SWC with WAM1and WAM2 is shown in Fig. 9. It demonstrates that the spatial patterns of moisture contribution between WAM1 and WAM2 match quite well with each other.

4.2 On ERA-I data

ERA-I, as a modern reanalysis, has significantly improved in comparison to its prior version, ERA-40 (https://climatedataguide.ucar.edu/climate-data/era-interim; Trenberth et al., 2011). The ERA-I variables differ according to whether they are produced by the analysis or the forecast. The analysis fields are constrained by the observations while the forecast are produced by the model (Berrisford et al., 2011; Dee et al., 2011). Thus, observation-constrained fields as humidity, wind, etc., tend to be more reliable than those from model forecast as precipitation, evaporation, etc. (Berrisford et al., 2011), so does the moisture transport derived from humidity and wind directly. In a comparison among several reanalyses (Trenberth et al., 2011), the long-term variation in moisture transport with ERA-I is rather stable which gives us more confidence in its application.

As in the study, observation-based precipitation (from CMA) and evaporation (GLDAS, forced with precipitation gauge observations) instead of their ERA-I forecast counterparts were used. On one hand, the input data for WAM becomes more accurate which facilitates more accurate results. On the other hand, changes in the ERA-I water cycle may induce changes in moisture origin and may further affect the trend results. In that consideration, moisture tracking for the SWC precipitation with the original ERA-I evaporation and precipitation is also performed. The basic results are shown in Fig. 10. The basic patterns of moisture contribution with different E and P are similar (cf. Fig. 3a and 10a), except that sources with ERA-I E and P tend to contribute more moisture, since the SWC precipitation in JAS is higher with ERA-I than with CMA (see Fig. 2b). The major region (enclosed by the 0.27 mm mon^{-1} red line in Fig. 3a) contributes 89.4% with ERA-I E and P. The trend patterns are generally the same between both datasets (cf. Fig. 3b and Fig. 10b). Though there are small differences in the magnitude of the rate and sometimes in rate signs over a few grids, the "East-increase and West-decrease" pattern remains unchanged. Thus, the major conclusions based on results with changed E and P remain unchanged. Instead, the application of CMA and GLDAS data tend to provide more reliable estimations. The small influence of evaporation and precipitation on the other hand highlight the importance of moisture transport. It is mainly due to the change in moisture transport that redistributes moisture, and leads to changes in moisture contributed to SWC as well as precipitation there.

~~4~~5 Conclusions

~~Summer~~ JAS precipitation over SWC has decreased significantly during 1979–2013. By tracing ~~moisture~~ the origins of moisture for JAS precipitation ~~in the summer months (July, August, and September)~~ and by analyzing the variations of moisture transport to SWC, we came to the following conclusions.

(1) Most moisture for the ~~SWC summer~~JAS precipitation in SWC originates ~~from~~in regions from the northern Indian Ocean to SWC and from South China Sea to SWC ~~the Asian monsoon regions~~. The westerlies play a secondary role in supplying moisture. The extended west region, SWC, and the extended east region contributes 48.2%, 15.5% and 24.5% of moisture to the JAS precipitation in SWC ~~summer precipitation~~, respectively. The Tibetan Plateau region contributes ~~a small portion (~~11.5%~~)~~ of the ~~precipitation~~ moisture for precipitation.

(2) The decrease in the ~~summer~~ JAS precipitation is mainly attributed to the reduced moisture supply from the extended west region. Moisture supply from the extended west region has decreased at a high rate (-~~23.6~~7.9 mm mon^{-1} decade^{-1}), and that from the extended east has increased at a low rate (~~4.2~~1.4 mm mon^{-1} decade^{-1}), resulting in an overall decrease of the moisture supply.

(3) The change in the stationary component has reduced moisture transport into SWC in JAS whereas the change in transient component has increased moisture transport ~~in summer~~ during 1979–2013. The dynamic processes (i.e., changes in ~~circulation~~wind) ~~is~~ are more important than the thermodynamic processes (i.e., changes in specific humidity) in affecting the precipitation. A prevailing easterly anomaly ~~of moisture transport~~ that weakened moisture transport ~~supply~~ from the Indian

Ocean is mainly responsible for the decrease of the SWC precipitation. The change in circulation may ~~is likely~~be related to the recent sea surface temperature change and need further investigation.

~~5~~6 Data availability

The ERA-I data are ~~available from~~supplied by ~~the European Centre for Medium-Range Weather Forecasts (~~ECMWF~~)~~ and are accessible at http://apps.ecmwf.int/datasets/data/interim-full-daily/. The GLDAS data are supplied by~~available from~~ the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) and are accessible at https://disc.sci.gsfc.nasa.gov/services/grads-gds/gldas. The CMA precipitation dataset is provided by China Meteorological Data Service Center (CMDC) and is accessible at http://data.cma.cn/en. The GLOBE elevation data are downloaded from https://www.ngdc.noaa.gov/mgg/topo/globe.html.

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

Acknowledgements. This work was supported through the National Natural Science Foundation of China (41425002), the Key Research Program of the Chinese Academy of Sciences (ZDRW-ZS-2016-6-4), and the National Youth Top-notch Talent Support Program in China. Support from Swedish VR, STINT, BECC, MERGE and SNIC through S-CMIP are also acknowledged.

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Table 1. The monthly precipitation trends (mm month^{-1} decade^{-1}) in SWC during 1979 to 2013. The P-values of the trends were calculated based on the two-tailed Student's t-test.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Trend	0.2	-1.4	1.3	0.1	3.7	-1.9	-5.0	-10.7	-10.0	-1.6	-1.4	-0.5
P-value	0.79	0.27	0.41	0.97	0.28	0.50	0.32	0.06	0.01	0.55	0.49	0.61

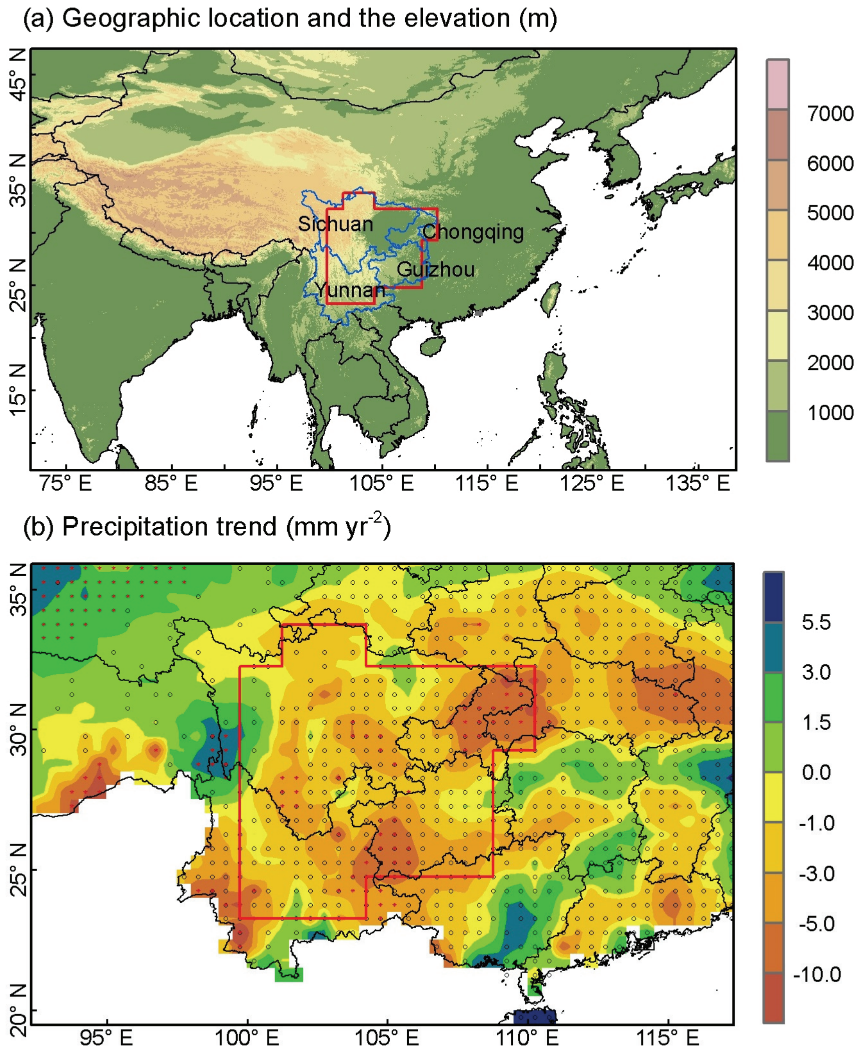

Figure 1. (a) Geographic location of SWC (red box). The blue lines delineate the major provinces/municipality within SWC. (b) The trend of annual precipitation in SWC from 1979 to 2013 with the CMA precipitation. The circles indicate the 0.5° grids with at least one rain gauge in 1979. The red dots denote the precipitation trends with significance at the 5% level.

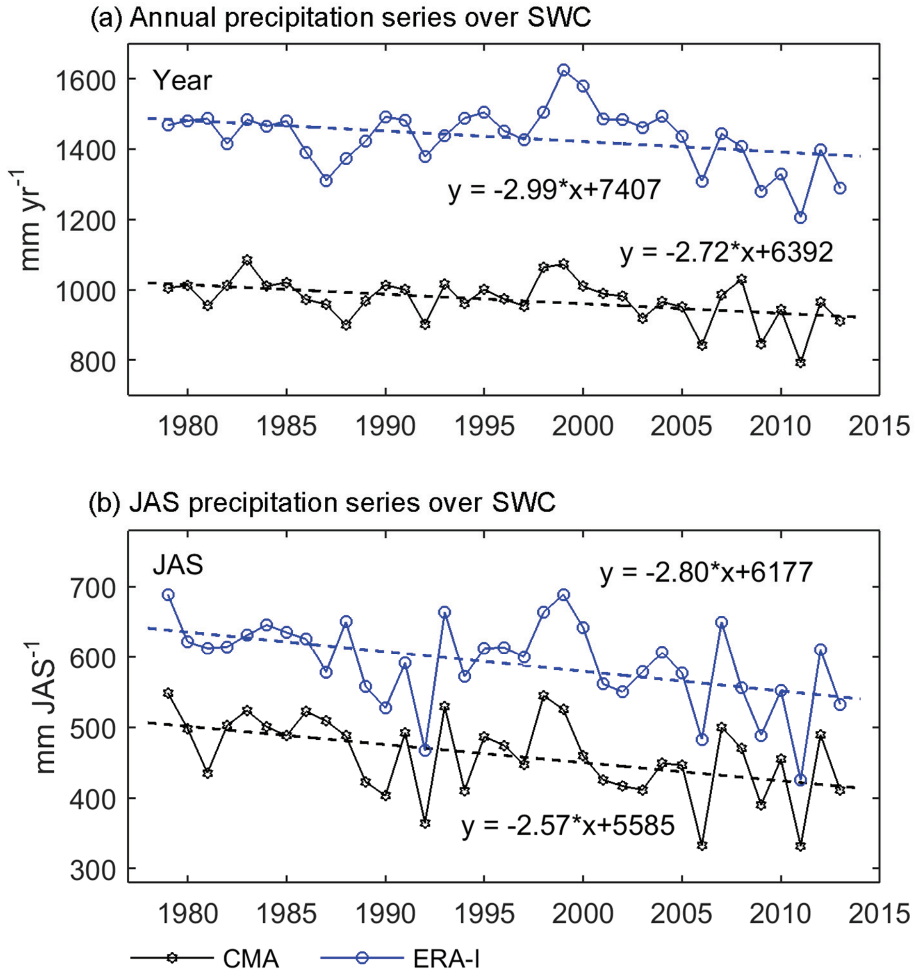

Figure 2. The time series of (a) annual and (b) July, August, and September (JAS) SWC precipitation from 1979 to 2013 with ERA-I (blue line) and CMA (black line) data. The trends are all significant at the 5% level based on the two-tailed Student's t-test.

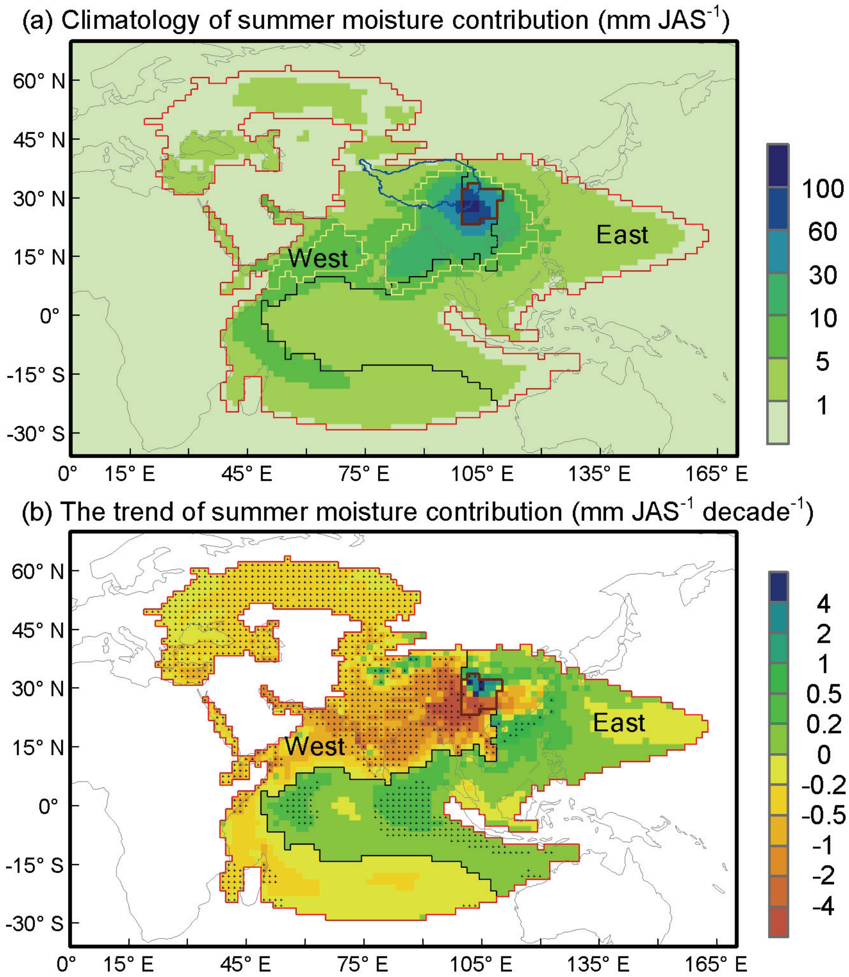

Figure ~~2~~3. (a) Climatology of the July, August, and September (JAS) ~~summer~~ moisture contribution to the SWC precipitation from 1979 to 2013. The red line delineates the major source region~~,~~ (i.e., grids with value above 0.~~8~~27 mm ~~yr~~mon^{-1}) which contributes 88.3% of the JAS precipitation moisture in SWC. The yellow line delineates the 50% moisture contribution areas with the grid values over the threshold of 2.35 mm mon^{-1}. The black line divides the major source region into the extended west, SWC, and extended east regions. The blue line delineates the Tibetan Plateau (Zhang et al., 2014). (b) The trend of the ~~summer~~ JAS moisture contribution from 1979 to 2013. The dots indicate a trend at the 5% significance level based on the t test. Values outside the major region are not shown.

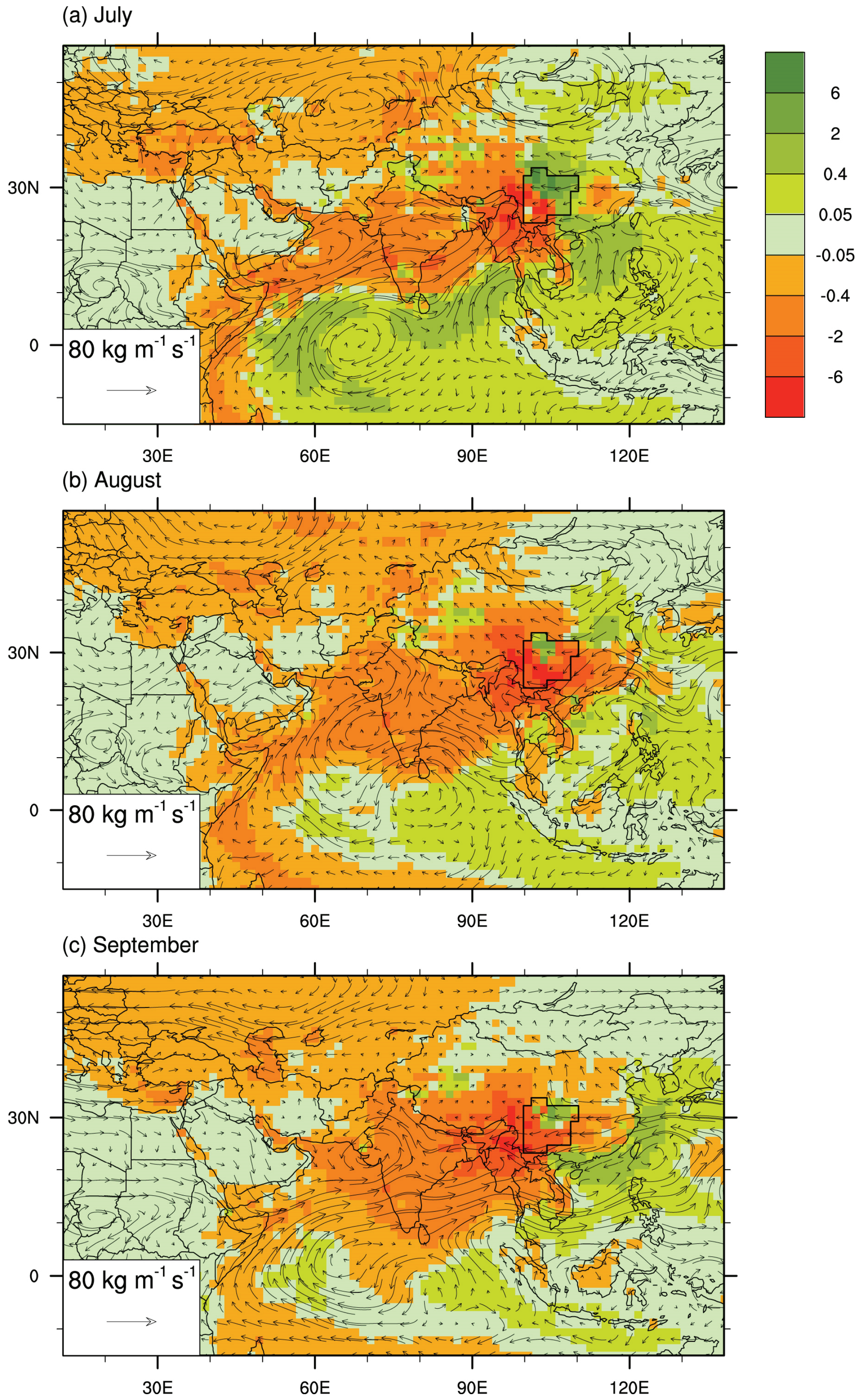
(a) July
(b) August
(c) September
80 kg m-1 s-1
30N
0
30E
60E
90E
120E
6
2
0.4
0.05
-0.05
-0.4
-2
-6

Figure ~~3~~4. The difference of mean moisture contribution (unit: mm month^{-1}; shading) in July (a), August (b), and September (c) ~~moisture contribution (unit: mm mon^{-1}; shading)~~ between ~~the last~~2004-2013 and ~~first 10 years (last – first) of~~ 1979–~~2013~~1988. The vectors represent the difference of moisture transport.

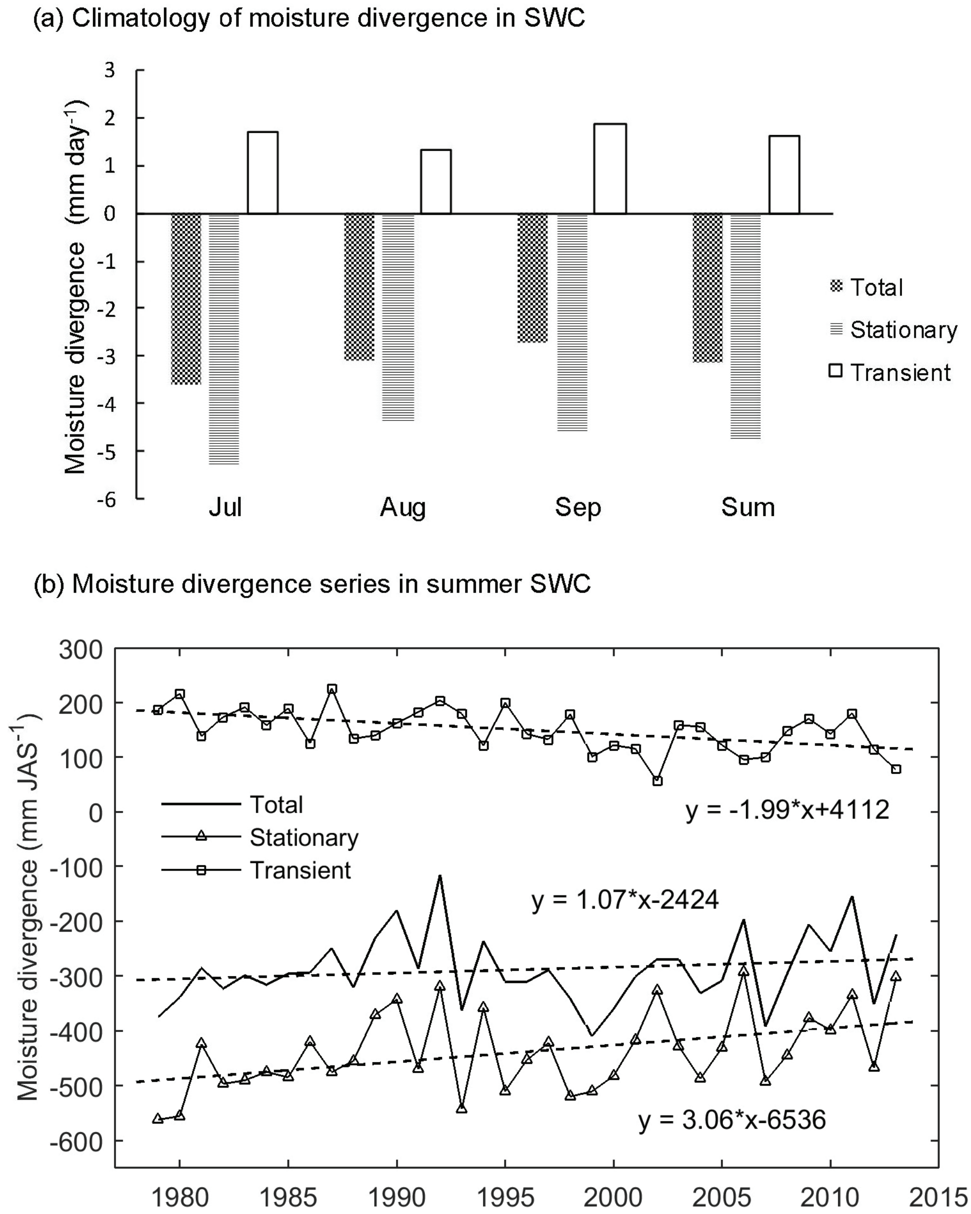

Figure ~~4~~5. (a) Areal moisture divergence and its stationary and transient components over the SWC (unit: mm ~~day~~mon^{-1}) for July, August, and September~~, and summer~~ during 1979–2013. (b) ~~Annual summer m~~Moisture divergence in JAS and its stationary and transient components (unit: mm mon^{-1}) over the SWC during 1979–2013.

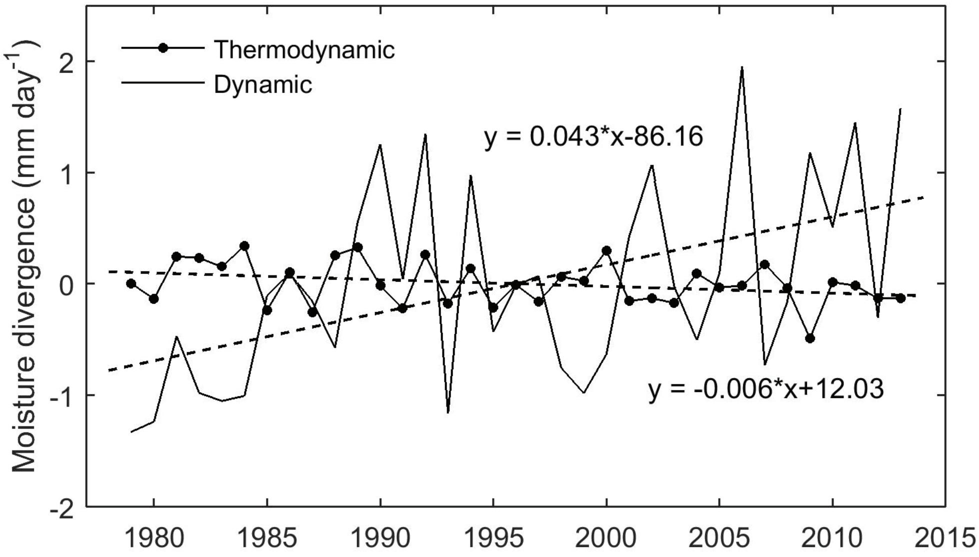

Figure ~~5~~6. The anomalies of ~~areal summer (from July to September)~~ moisture divergence over ~~the~~ JAS SWC (unit: mm ~~day~~mon^{-1}) caused by thermodynamic and dynamic terms during 1979–2013.

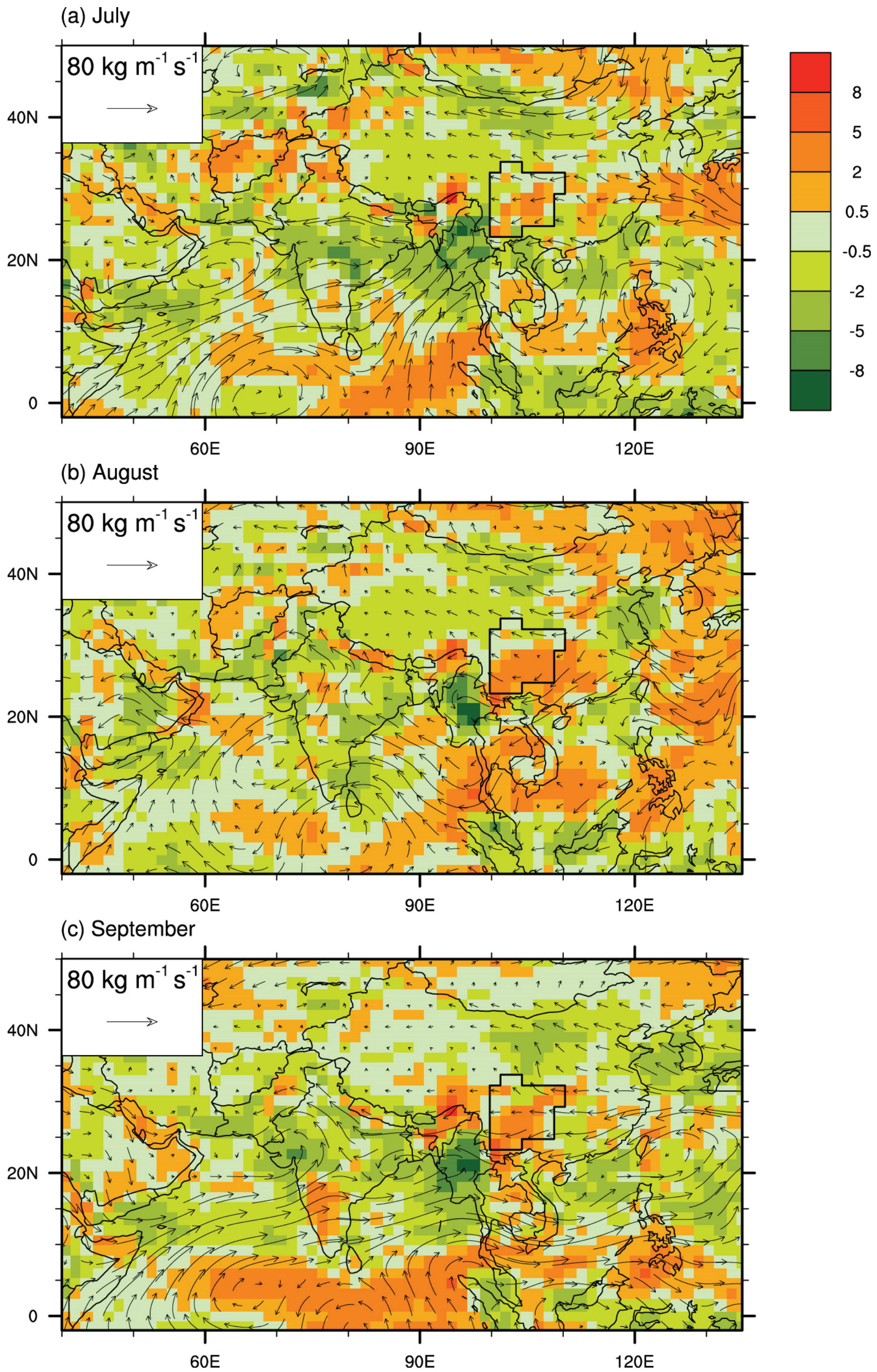

Figure ~~6~~7. The monthly difference flux (vectors) of the dynamic component of the stationary moisture transport between the last and first 10 years (last – first) and its divergence (unit: 10^{-5} kg m^{-2} s^{-1}; shading).

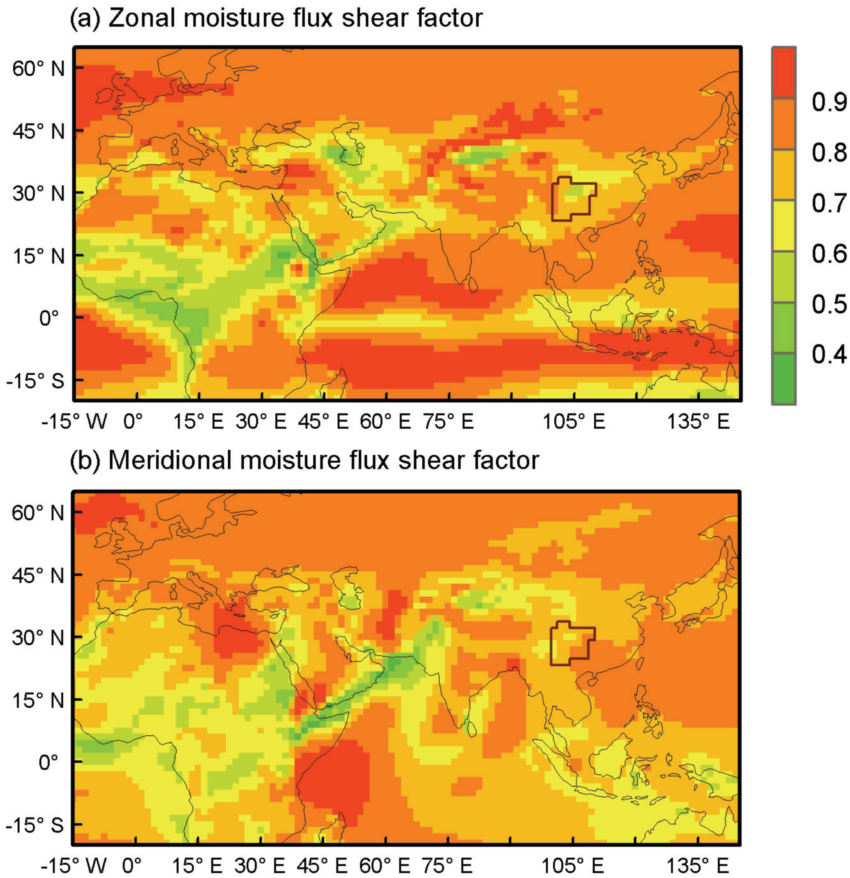

Figure 8. Horizontal moisture flux shear factor in JAS averaged over 1979–2013 with ERA-I. (a) Zonal moisture flux shear factor, (b) meridional moisture flux shear factor.

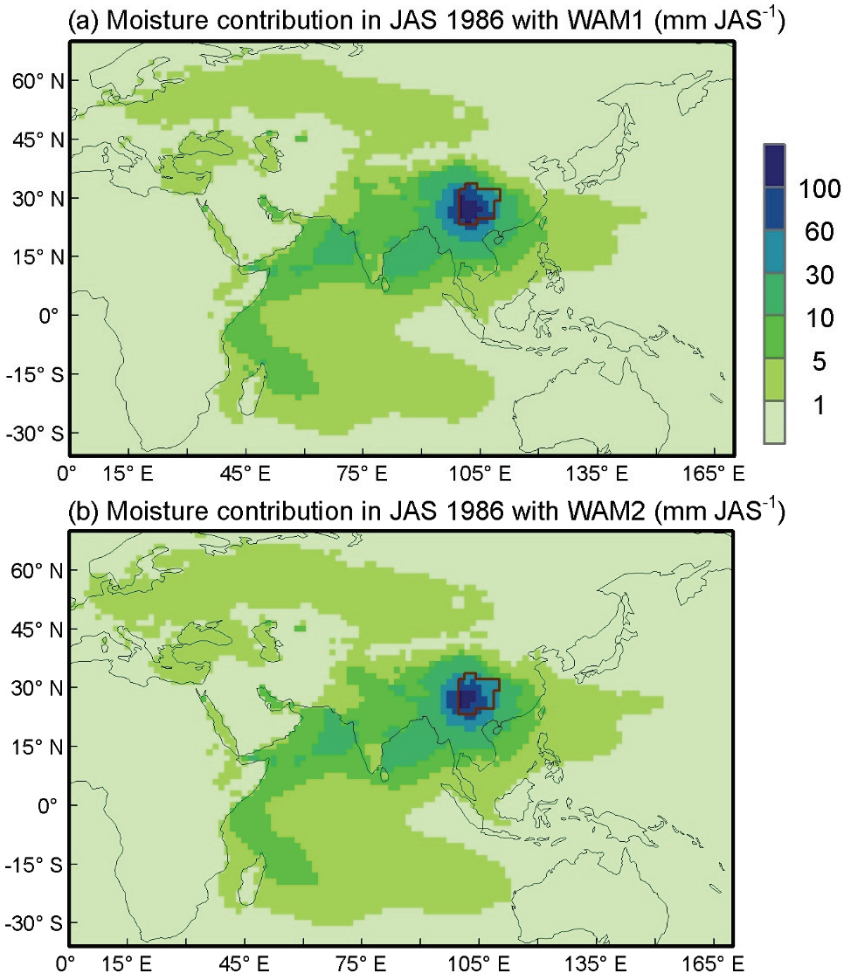

Figure 9. Moisture contribution of the SWC precipitation in JAS, 1986 with WAM1 (a) and WAM2 (b).

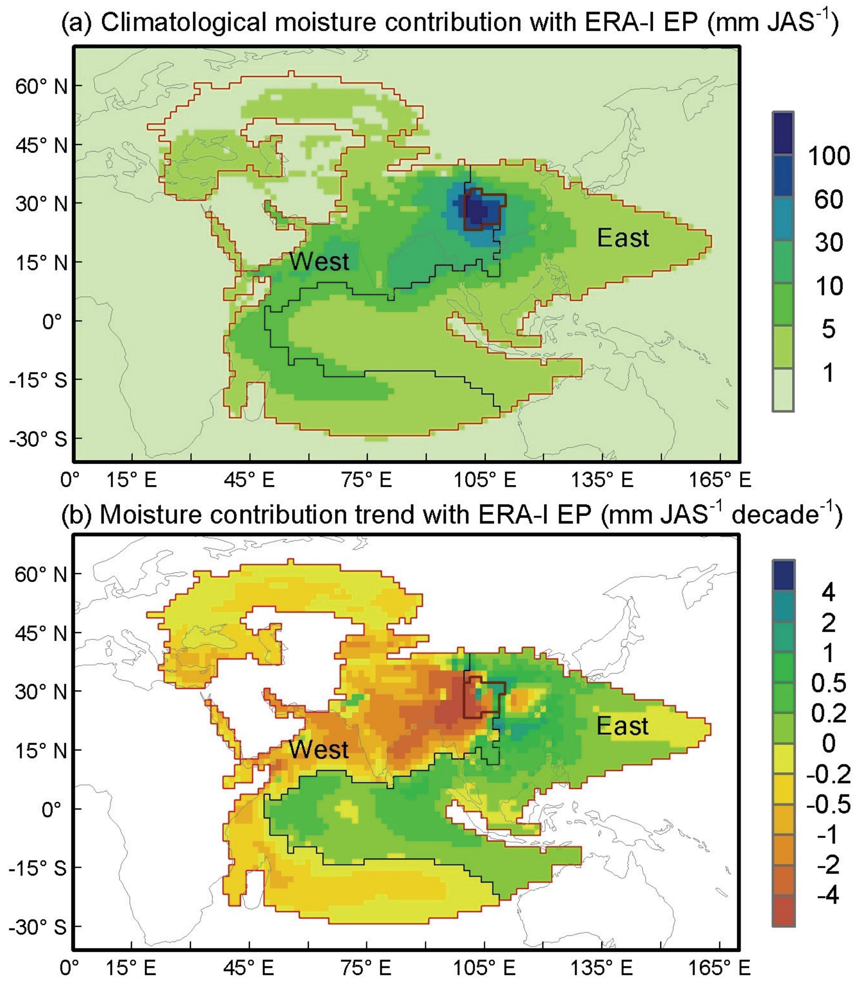

Figure 10. (a) Climatology of the JAS moisture contribution to the SWC precipitation from 1979 to 2013 with ERA-I E and P. (b) The trend of the JAS moisture contribution from 1979 to 2013 with ERA-I E and P. The red line and East-West division are the same as in Fig. 3.