Response to the editor:

Editor Decision: Reconsider after major revisions (15 Mar 2016) by Dr Luis Samaniego
Comments to the Author:
1) I appreciate the reply provided by the authors but I hardy find in their revised manuscript what has been done. Authors mentioned, e.g.,

"Reply: Thank you for your advice. We will address the points in the revised paper accordingly." I wonder what was done? Where? Please indicated with page and line number, or highlighted text what has been done to address reviewers comments.

Reply: We have added the paragraphs and the sections where we have made the revision in the response files to the two reviewers.

2) I wonder which tests have been performed to find the causality chain proposed in Fig 8. I guess this is the main goal of this paper and should be highlighted in the introduction. Introduction is too short in my opinion. No in depth literature review.
Reply: To see which part of global oceans plays a key role in the Sahel rainfall variation, we have made new Figure 8 representing the trend shift vector map of the horizontal moisture flux. This figure observes that the south of Indian Ocean and the east of the Pacific Ocean play a key role in Sahel rainfall variation. We have added it to the revised manuscript in the third paragraph of Section 3.4 and the first paragraph of Section 4.

3) Authors should formulate a system of hypotheses and a way to test it.

Reply: Based on new Figure 8 along with LHF, the south of Indian Ocean and the east of the Pacific Ocean play a key role in Sahel rainfall variation. We have added it to the revised manuscript in the third paragraph of Section 3.4 and the first paragraph of Section 4. In addition, to show another evidence of the trend shift of HLF, we have added latent flux trend shift map based on another reanalysis dataset (JRA-55) in the revised version (See new Figure 5a and b). Even in the JRA-55 dataset, the overall pattern of the trend shift is seen although there are some different areas.

Reply to Referee 1's comments on the manuscript entitled "Synchrony of trend shifts in Sahel summer rainfall and global oceanic evaporation, 1950–2012" by Alima Diawara, Yoshihiro Tachibana, Kazuhiro Oshima, Hatsumi Nishikawa and Yuta Ando

Overview:
This paper described a multi-decadal link of boreal summer rainfall over Sahel region with the global oceanic evaporation by using long-term observation and reanalysis data. The analysis of global climate fields suggested that a recent positive shift in the Sahel rainfall variability may be induced by the increased oceanic evaporation in both the Northern and Southern Hemisphere. The results shown here are interesting and the paper is well written, but a detailed mechanism behind the multidecadal link between the Sahel rainfall and the global oceanic evaporation is not clearly examined. Also, the relation between the global SST and LHF variability are not fully investigated in the relevant figures. These issues should be carefully addressed to improve our historical understanding of the multidecadal rainfall variability over Sahel region. Therefore, this paper requires major revision before possible publication. Below are the major and specific comments on this paper.

Reply:
Please accept our sincere appreciation for your valuable comments on our manuscript, which has led us to improve the quality of our paper.

Major comments:
1. Multi-decadal link between the Sahel rainfall and the global oceanic evaporation (Section 3.1). In the introduction section, the authors clearly stated that understanding the source of Sahel rainfall should help explaining the variation, but they did not perform any detailed analysis for the source of Sahel rainfall variability. Although the multi-decadal link between the Sahel rainfall and the global oceanic evaporation was mainly discussed in this study, a detailed mechanism behind the source of Sahel rainfall variation is not well studied. Which part of global oceans plays a key role in the Sahel rainfall variation? How does the evaporation over the above ocean affect the Sahel rainfall variability? The authors should provide more detailed information on the source of Sahel rainfall variability.
Reply:
Thank you for this comments. As in you mentioned, our previous version did not capture the "exact source" that remotely influences on the Sahel rainfall. In order to see which part of global oceans plays a key role in the Sahel rainfall variation, we have added a new figure (Figure 8) and additional description. Figure 8 represents the trend shift vector map of the horizontal moisture flux. In addition this figure demonstrates the key role the south of Indian Ocean and the east of the Pacific Ocean play in Sahel rainfall variation. As observed, a weaker transport from North Atlantic through Mediterranean

ocean entrance to Libya is also observed but blocked by the local high pressure located in the Sahara desert. We have also added a description of our observation on the revised manuscript in the third paragraph of Section 3.4 and the first paragraph of Section 4.

To better highlight our point, we have cited valuable researchers work such as Giannini et al. (2003) and Zeng (2003). Giannini et al. (2003) and Zeng (2003) hypothesized that moisture flux from the South Indian and the East Pacific ocean and the subtropical Atlantic ocean in the southern hemisphere transport toward the Sahel region. As a result our moisture flux figure has confirmed their hypothesis: the transport pattern from East Pacific through Caribbean to tropical Atlantic toward West Africa, and from the South Indian Ocean to the southern Atlantic ocean, and entering the West Africa. This key point have been added it to our revised manuscript in the first paragraph of Section 4.

*2. Role of oceanic evaporation in the SST variability (Sections 3.2-3.4) the link between the SST and LHF variability is still unclear. The authors claimed that in the Northern Hemisphere, the positive shift in the SST variability induces the positive shift in the LHF variability. However, this is not evident in the zonal mean figure, where the SST variability north of 40 ◦ N clearly shows the negative shift (Fig. 4). Also, the authors mentioned that in the Southern Hemisphere, the positive shift in the wind variability contributes to the positive shift in the LHF variability. But, it is hard to see the positive shift in the wind variability, because the wind variability represents opposite signs north and south of 20 ◦ S (Fig. 6). Furthermore, the negative shift in the SST variability cannot be clearly seen north of 50 ◦ S. The authors should carefully describe regional differences in the multidecadal variability among the variables.*Reply:

We absolutely concur with this comment. In fact the previous Figs. 5, 6 and 7 were inaccurate due to the calculation of the zonal mean graphs and the treatment of the missing data. As a result we have corrected the figures with additional approaches in our revised manuscript. This error is the main reason our previous Figures and descriptions were inconsistent. As described in Fig 5 of our revised manuscript the trend shift in oceanic evaporation contains the SH and the subtropical NH, including the Pacific, Atlantic, and Indian Ocean. Since increased oceanic evaporation strengthens global moisture transport toward the land, the synchronization of these trend shifts is physically plausible, therefore the area of increased LHF exceeded the area of decreased LHF. The surface scalar wind over the ocean had a positive trend shift, mainly in the SH, that extended to the subtropical Pacific Ocean in the NH (Fig. 6). The humidity deficit displayed a positive trend shift in both hemispheres, particularly in the Pacific Ocean (Fig. 7).

3. Data quality before the satellite era, there is ample evidence that the observational data in the Southern Hemisphere before the satellite era are not as reliable as those in the Northern Hemisphere, but the authors elaborated on the multidecadal link with the Southern Hemisphere before the satellite era as well. The multidecadal link with the Southern Hemisphere should be focused in the recent *satellite era. Rather than the Southern Hemisphere, the neighboring oceans such as the tropical Atlantic and North Atlantic Oceans would have a major role in the multi-decadal rainfall variability because of proximity to Sahel region.*

Reply:

We absolutely agree with the fact that the observational data in the Southern Hemisphere before the satellite era are not as reliable as those in the Northern Hemisphere, and recent data sets are much more reliable estimations. Therefore we recognize that the reliability and the choice of the data are crucial in a specific study. To clarify our results based on new evidences in the revised version, we have added latent flux trend shift map based on another reanalysis dataset (JRA-55) (Refer to new Figure 5a and b). In the JRA-55 dataset, the overall pattern of the trend shift is seen although there are some different areas.

4. P11270 L1: "summer" should be "boreal summer".

Reply:

Thank you for the suggestion. We think that the boreal summer is much appropriate for the purpose of the study.

5. *L4-6:This argument is very strong and needs to be modified with further analysis.*

Reply:

Thank you for this valuable comment. In our revised version we have provided further analysis which points out that this trend shift was synchronous with similar trend shifts in global oceanic evaporation (Figs. 2 and 4) and in land precipitation in all continents except the Americas (Fig. 4).

6. *L7-9: Analysis of moisture flux would be helpful for identifying whether the anomalous moisture advects over the continent or not.*

Reply:

We have added the trend shift map of the moisture flux (new Figure 8), and have added the explanation on the results in section in the section 3.4.

7. *P11271 L21-24: Did the authors compare their results with other available rainfall data (e.g. GPCC)?*

Reply:

To compare our results with other available rainfall data, in our revised manuscript we have added Figure 3a, c and d of JAS trend shift using PREC_L, GPCC and University of Delaware data set respectively and figure 3b of annual trend shift using PREC_L data set. As a result we are seeing a similar pattern and impact coverage (hatching is $\tan\theta_1 \cdot \tan\theta_2 < 0$) on PREC_L, GPCC, and a stronger coverage on PREC_L data while a weaker coverage on University of Delaware is observed. We used the annual trend shift using PREC_L to illustrate the importance of JAS pointing the raining season in Sahel region.

8. *P11272 L17-25: The defined box does not cover major Sahel rainfall region. I do not understand why the authors used the box covering only half of the boreal summer rainfall peak, although the signature is not sensitive to the definition.*

Reply:

As you pointed out, the Sahel region defined in this study do not cover the peaks of summer rainfall and its standard deviation, but this area clearly shows high contribution of summer rainfall to the annual rainfall in this region as shown by Figure 2a in Cairns et al. (2012). Another key reason for that is that we defined the Sahel region removing the direct influence of Atlantic and Indian Ocean over the coast line up to 100km. in addition, the large positive sign of the JAS precipitation trend shift are seen over this region (Fig. 3). We added these explanation in the second paragraph of Section 2 of our revised manuscript.

9. *P11277 L4-6: This sentence seems to have nothing to do with the purpose of this study.*

Reply:

The modification has been done as suggested.

References:

Zhang GJ, Mcphaden MJ (1995). The relationship between sea surface temperature and latent heat flux in the equatorial Pacific. J Clim 8(3):589–605.

Wu R, Kirtman BP, Pegion K (2009). Surface latent heat flux and its relationship with sea surface temperature in the National Centers for Environmental Prediction Climate Forecast System simulation and retrospective forecasts. Geophys Res Lett 34:L17712. doi:10.1029/2007GL030751

Zeng, N. (2003), Drought in the Sahel, Science, **302**, 999–1000.

Giannini, A., R. Saravanan, and P. Chang (2003), Oceanic Forcing of Sahel Rainfall on Interannual to Interdecadal Time Scales, Science, 302(5647), 1027-1030, doi:10.1126/science.1089357.

Reply to Referee 2's comments on the manuscript entitled "Synchrony of trend shifts in Sahel summer rainfall and global oceanic evaporation, 1950–2012" by Alima. Diawara, Yoshihiro. Tachibana, Kazuhiro. Oshima, Hatsumi. Nishikawa and Yuta. Ando

Overview: Using reanalysis and observation-based datasets, authors examined the summer precipitation changes defined as the trend difference between 1950-1984 and 1985-2012 periods. In Sahel region, precipitation shows a drying trend for 1950-1984 but a wetting trend for 1985-2012. The similar trend shift is also found in latent heat flux anomalies averaged over the global ocean. Authors also pointed out that this trend shift in latent heat flux anomalies is consistent with a SST trend shift in the northern hemisphere and a wind speed shift in the southern hemisphere.

This result may have an important implication for global hydrological cycles that may also influence the Sahel rainfall variability. The good point in this manuscript is that authors clearly described what they did. However, I feel that this manuscript have to present their findings more logically. Although I can understand "what" they did, I cannot understand "why" they did it. Why does this manuscript examine the trend shifts in Sahel summer rainfall? Why did author take the Sahel region illustrated by the black box in Fig 1 and the period for 1950-1984 and 1985-2012? Why do we need to focus on the evaporation averaged over the "global" ocean instead of the "regional"? I would like to encourage them to revise this manuscript with more logical way instead of a description. The following is more detailed point that might be helpful to revise this manuscript.

Reply
We sincerely appreciate your input. We have addressed the points in the revised paper accordingly.

1. First, I cannot understand what is the main goal of this manuscript and what is the scientific question that authors want to clarify in this manuscript. In introduction, authors pointed out the local and remote SST effects on decadal rainfall variability over Sahel region. Based on these previous studies, authors described the current problem of previous studies: "the exact linkage between the multi-decadal variation of Sahel rainfall and the global ocean is unclear" on Line 10 Page 11271. So we expect that this *manuscript will reveal the exact linkage about multi-decadal rainfall variability. However, this manuscript examined the "trend shift" instead of multi-decadal variability. I confused why this manuscript focused on the trend shift and why did they choose trends for those specific periods.*

Reply:

Based on your input, we have turned our focus on the changes in Sahel rainfall that occurred in about 1985. Our approach is constrained by data availability and data quality. We are unable to study multi-decadal variability directly because there was only sufficient data to look at 1 or at most 2 cycles, therefore we focused on a phenomenon ("the trend shift") that might indicate a change in phase in multi-decadal variability. As you pointed out we did not describe why 1985 is not in the previous version. 1984 is the lowest year on the time series of Sahel precipitation, in the same time it is located at the middle of the sixty years change of tendency, as a result we took advantage of that in calculating the trend shift of before 1984 and after 1984. We have added this key point in our revised manuscript and in more details in section 2. We mistakenly wrote "multi-decadal variability". In the revised version, we have removed this term.

2. Second, I have no idea why they assumed that "moisture transport from different parts of the world ocean may have some effects on precipitation over Africa", as described on Lines 13-15 Page 11271. According to the moisture balance equation, the precipitation anomalies balance the moisture divergence and evaporation anomalies. This equation is based on the local process and I hesitate to assume that the evaporation variability in the Pacific affects to the Sahel rainfall. The tropical Pacific SST variability could induce changes in atmospheric circulation, which may influence the moisture flux divergence over Sahel region. So I can agree that the global SST variability plays some roles for Sahel rainfall variability. However, it is not make sense for me that the evaporation in the tropical Pacific affects Sahel rainfall variability via moisture transport.

Finally, there is no scientific evidence to explain the possible physical linkage as summarized in schematic diagram in Fig 8. According to this manuscript, the SST trend shift induces the trend shift of latent heat flux in the northern hemisphere whereas the wind speed trend shift contributes to trend shifts of latent heat flux and SST in the southern hemisphere. In other words, this manuscript assumes that changes in all of those variables are in phase. However, the latent heat flux anomalies (and wind speed anomalies) contribute to "tendency" of SST anomalies, which means that the SST *anomaly change would be out of phase compared to changes in wind speed or latent heat flux anomalies. More logical explanation for this manuscript would be needed.*

Reply:

“Second…… over Sahel region”: The summary of the comment is why we assume a connection between global evaporation and local rainfall. In the introduction part of the revised version, we have expanded our discussion of the literature cited in this sentence: "Sahel rainfall is known to be related to nearby SST (Lough, 1986; Bader and Latif, 2003; Chung and Ramanathan, 2006) and remote SST (Folland et al., 1986; Janicot et al., 1996; Rowell, 2003; Fontaine et al., 2011; Munemoto and Tachibana, 2012; Diatta and Fink, 2014)." The fact that the Sahel rainfall is correlated with "remote SST" suggests that global-scale processes are potentially important, and it is not just an assumption that we have made. We have added the trend shift map of horizontal moisture flux in new Figure 8. In this new figure we can see that the moisture transport from the south of the Indian Ocean and the east of the Pacific Ocean, and that this flux pattern may play a key role in Sahel rainfall variation. A weak transport from North Atlantic through Mediterranean ocean entrance to Libya is also observed. This new observation have been added to the manuscript in the section 3.4 and section 4.

“Finally...anomalies.” Thank you for your great advice. The time change of the SST, i.e., SST trend, should be linearly related to the evaporation from the ocean as in the thermodynamic formula, therefore time change of the evaporation, i.e., LHF trend, should be linearly related to the second-order differential of the SST. We simply compared between the two trend shifts. Unfortunately, the quality of the global dataset does not resolve the second-order differential. In the revised manuscript, we have included this point in the section 3.3.

3. Didn't Zhang and Delworth (2006) demonstrate that Sahel rainfall is strongly correlated with the Atlantic Multi-decadal Oscillation? In that case, the trend shift could be explained by whatever is responsible for the AMO. That is the missing teleconnection. What does this study tell us that we do not learn from Zhang and Delworth (2006)?

Reply:

Thank you for your suggestion on the AMO. As you pointed out, Zhang et al. 2006 indicated the relationship between the low frequency SST anomalies averaged over the Atlantic i.e. AMO and Sahel summer rainfall. In addition to that, we think that there is some oceanic influence from outside of the Atlantic. AMO could probably be a cause of the trend shift, but influence of other oceans are additional cause as in our results. In the revised manuscript, the consistency with Zhang et al. 2006 has been added in the second paragraph of the introduction.

4. Could you please show (not merely say) that the differences in the reanalysis datasets do not matter for this analysis?

Reply:

The dependence in the choice of the dataset is real but not crucial. In the revised manuscript, we use JRA-55 and NCEP data to summarize the dependence on the choice of used dataset and NCEP is the closest appropriate for this study. Figure 3, and 5 are based on different source of data sets, we could see that the Figure 3 of precipitation using PREC_L, GPCC and University of Delaware data sets are similar, while Figure 5 of JAS trend shift of LHF using NCEP and JRA-55 diverge only over the south tropical Atlantic Ocean. The results of the dependence on the used dataset have been added in section 3.2 and 3.3.

5. Lines 22-23 Page 11270 "Many studies have shown that rainfall varies greatly in the Sahel": This sentence is unclear. Does Sahel have the largest precipitation variance over land? What timescale do you want to say?

Reply:

As we mentioned in the revised manuscript, the Sahel region does not have the largest precipitation variance over land, however the tendency of it precipitation times series have shown a tremendous change over the last sixty years that cannot neglected as shown on Figure 2. This fact had been reported by a several previous research papers (e.g., Hulme, 1992, Christensen et al., 2007, Baines and Folland, 2007). In the revised manuscript, we pointed out the behavior of the tendency (trend shift) and took advantage of the picks in the trend shift factor.

6. Line 9 Page 11271 "long-term climate trends are generally related to the state of the ocean": This sentence is unclear. We may say that a long-term temperature trend is generally related to atmospheric CO2 increase. But I don’t know what kind of long-term climate trends authors want to say.

Reply:

In the revised manuscript, we have clarify this sentence which refers to the oceans affect atmospheric circulation, weather and climate in general. Our focus is not the increase of the CO2 effect, but the trend shift during the past six decades. We have added it in the second paragraph in the introduction section.

7. Lines 13-15 Page 11271 "It is reasonable that ..." As I described in my major comment, this is not reasonable for me.

Reply:

We have considered all part of the oceans map and confirmed previous studies such as Omotosho et al 2008. Omotosho et al 2008 research focuses on the change in ITCZ position or the storm track. An additional example is Giannini et 2003 research which investigates the global oceanic warming over Africa. Considering the fact that the oceanic evaporation increases water vapor in the atmosphere, this may enhance moisture transport and has an important role to play into Africa. In fact, Sahel region could explain some lacks of understanding the actual phenomenon in the region. In our revised manuscript, We have further addressed this point in the first and second paragraphs of introduction section.

8. Line 18 Page 11272 "defined as the region ..." Why do authors define this region? It may be good idea to show the standard deviation or variance for precipitation.

Reply:

This is similar to the comment #8 of Referee 1. As you pointed out, the Sahel region defined in this study does not cover the peaks of summer rainfall and its standard deviation, but this area clearly shows high contribution of summer rainfall to the annual rainfall in this region as shown by Figure 2a in Cairns et al. (2012). Another reason is that we defined the Sahel region removing the direct influence of Atlantic and Indian Ocean over the coast line up to 100km. In addition, the large positive sign of the JAS precipitation trend shift is seen over this region (Fig. 3). In our revised manuscript, we have added these explanation in the second paragraph of Section 2.

9. Line 10 Page 11274 "SST decreased until 1984" From the spatial map of SST trends difference, I cannot see the SST decreasing until 1984.

Reply:

Reddish areas with hatching are overall cover in the northern hemisphere. Hatching with reddish area means that the sign of trend changed from negative to positive. We omitted detailed description on this. This description has been added in the Section 3.2 of our revised manuscript.

References:

Wu R, Kirtman BP, Pegion K (2009) Surface latent heat flux and its relationship with sea surface temperature in the National Centers for Environmental Prediction Climate Forecast System simulation and retrospective forecasts. Geophys Res Lett 34:L17712. doi:10.1029/2007GL030751

Synchrony of trend shifts in Sahel boreal summer rainfall and global oceanic evaporation, 1950–2012

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Abstract

Between 1950 and 2012, boreal summer (rainy season) rainfall in the Sahel changed from a multi-decadal decreasing trend to an increasing trend (positive trend shift) in the mid-1980s. We found that this trend shift was synchronous with similar trend shifts in global oceanic evaporation and in land precipitation in all continents except the Americas. The trend shift in oceanic evaporation occurred mainly in the southern hemisphere (SH) and the subtropical oceans of the northern hemisphere (NH). Because increased oceanic evaporation strengthens the atmospheric moisture transport toward land areas, the synchrony of oceanic evaporation and land precipitation is reasonable. Surface scalar winds over the SH oceans also displayed a positive trend shift. Sea surface temperature (SST) displayed a trend shift in the mid-1980s that was negative (increasing, then decreasing) in the SH and positive in the NH. Although SST had opposite trend shifts in both hemispheres, the trend shift in evaporation was positive in both hemispheres. We infer that because strong winds promote evaporative cooling, the trend shift in SH winds strengthened the trend shifts of both SST and evaporation in the SH. Because high SST promotes evaporation, the trend shift in NH SST strengthened the NH trend shift in evaporation. Thus differing oceanic roles in the SH and NH generated the positive trend shift in evaporation; however, the details of moisture transport toward the Sahel are still unclear or perhaps there is no single determining influence.

1 Introduction

~~The~~ For the past sixty years, the West African Sahel region, ~~the area of western Africa~~located between 10°N ~~and~~– 20°N~~, commonly suffers from severe drought and is synonymous with unstable~~ longitude, has been one of the most important research areas for studying climatic variability due to its fragile climate ~~(Dai, 2011). Many studies have shown that rainfall varies greatly in~~ conditions. While there are many well-documented analyses of the Sahel~~.~~'s drought conditions since the early 1970s (e.g., Hulme, 1992, Christensen et al., 2007, Baines and Folland~~ et al. (1986) established a relationship between Sahel rainfall and hemispheric disparity in sea surface temperature (SST)~~, 2007), there is no general explanation on ~~multi-decadal time scales, such that when SST is higher (lower) than normal in the southern hemisphere (SH) and lower (higher) than normal in the northern hemisphere (NH), the Sahel is drier (wetter) than normal.~~the source of the drought. Several studies have also shown that the Indian Ocean, the North and South Atlantic~~,~~ Ocean, and the southern hemisphere (SH) oceans and the Mediterranean Sea have, alone or together, some kind of remote influence on the distribution of Sahel rainfall (Palmer, 1986; Giannini et al., 2003; Wolter, 1989; Janicot et al., 1996; Rowell, 2003; Hagos and Cook, 2008; Diatta and Fink, 2014). ~~Munemoto and Tachibana (2012), using updated datasets, confirmed the relationship of Folland et al. (1986) and also showed that correspond to the more recent pattern of Sahel rainfall, which shifted from a decreasing trend to an increasing trend in the mid-1980s.~~

~~Although long-term climate trends are generally related to the state of the ocean, the~~ Studies and evaluations of the Sahel monsoon are crucial to determine previous precipitation variations, provide climate projections, and offer a scientific response to the decrease in rainfall over the majority of the region (Dai et al., 2001, Omotosho et al., 2008); however, the exact linkage between the multi-decadal ~~variation~~variations of the Sahel rainfall and the global ocean ~~is~~remain unclear. ~~Understanding the source of Sahel rainfall should help in explaining its variation. The~~ Sahel rainfall is correlated with remote SST, which suggests that global-scale ocean evaporation processes are potentially important for the historical land surface rainfall variability. Our initial analysis suggested that the global hydrological cycle ~~comprises~~is comprised of evaporation from some part of the ocean surface and the transport of water ~~vapour~~vapor over the ~~continents.~~African continent. Therefore, it is reasonable that moisture transport from different parts of the world ocean may ~~have some effects~~, either ~~singly~~alone or in combination, ~~on~~affect African precipitation ~~over Africa~~in general and that of the Sahel in particular. ~~In this study, we analysed datasets of global-scale evaporation~~

for the second half of the 20th century in an effort to demonstrate the relationship of the shift in Sahel rainfall to shifts in oceanic evaporation. We also sought insight into the causes of long-term variations in global oceanic evaporation.

Some of the earliest works related to nearby sea surface temperatures (SSTs) have shown that precipitation time's series have significantly changed over the last sixty years (Lough, 1986; Bader and Latif, 2003; Chung and Ramanathan, 2006). Other studies related to remote SST point out that the precipitation time's series has considerably changed over that the past sixty years as well (Folland et al., 1986; Janicot et al., 1996; Rowell, 2003; Fontaine et al., 2011; Munemoto and Tachibana, 2012; Diatta and Fink, 2014). The potential long-term causes and effects of SST variability are important inputs for the thermo-dynamical process of Sahel rainfall (Folland et al. 1986; Giannini et al. 2003; Tippett & Giannini 2006; Lu and Delworth 2005; Hoerling et al. 2006). Although long-term climate trends are commonly related to the state of the ocean, the radiative forcing by changing levels of greenhouse gas and/or aerosols have been considered responsible for the changes of climate in the global ocean and on each continent except Antarctica (Stott et al., 2010). Yet, the increased trend of the greenhouse gas has not been linked to the trend shift of the Sahel rainfall. Delworth et al. (1993) defined the thermal impacts of the North Atlantic thermohaline overturning flow at multi-decadal scales. Zhang and Delworth (2006) referred to the subsequent SST pattern as the Atlantic Multi-decadal Oscillation. Pomposi et al. (2015) examined the role of global SST anomalies and their effects on monsoon variability in the Sahel region and found that "much of the internal variability of the global monsoon system" is generated by SST variances and their outcome on the atmospheric teleconnections, linking oceanic variations to land-based rainfall. Munemoto and Tachibana (2012) demonstrated that the contrast between North and South SST also corresponds to the more recent pattern of Sahel rainfall; in the mid-1980s, the phenomenon shifted from a decreasing trend to an increasing trend. These various studies underscore the lack of a single mechanism determining the relationship between the shift of the Sahel rainfall and the shift of oceanic evaporation. Folland et al. (1986) were among the first to historically establish a relationship between Sahel rainfall and (SH) SST on multi-decadal time scales; this relationship has demonstrated that when the SH SST is higher (lower) than normal, the Sahel is drier (wetter) than normal (Folland et al., 1986). Bader and Latif (2003) considered the warming trend in the Indian Ocean to have "a crucial role for the [forty-year] drying trend over the West Sahel." As a consequence, Indian Ocean warming may have contributed to the strengthening of the North Atlantic Oscillation during these last two decades. In addition, their experiments highlight the influence of the tropical Pacific over the eastern Sahel, whereas the tropical Atlantic influences rainfall only over the Atlantic itself and along the western Sahel.

For this study, we analyzed global evaporation datasets for the second half of the 20th century in order to determine whether the previously established linkages between remote SST and Sahel rainfall are the result of remote linkages between Sahel rainfall and oceanic evaporation. We also investigated the underlying trends in wind stress and SST that may explain changes in evaporation. Given the region’s exposure to natural variability, favoring severe drought with unexplained sequence variations, this study will deliver a skillful multi-decadal climate forecast for the Sahel.

2 Data and Methods

For the precipitation~~ on land~~, we used 3 different monthly ~~data~~datasets: from 1949 to 2014~~ in~~, the National Oceanic and Atmospheric Administration (NOAA) Precipitation Reconstruction over Land (PREC/L) database (Chen et al., 2002) with a spatial resolution of 1.0 degree in latitude and longitude~~.~~; the Global Precipitation Climatology Centre (GPCC) data (Schneider et al. 2011), 2.5x2.5, from 1949 to 2013; and the University of Delaware UDel_AirT_Precip data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/, resolution of 0.5x0.5 and from 1949 to 2013. For SST, we used monthly data from 1953 to 2012 in the NOAA Extended Reconstructed SST Version 3 (NOAA ERSST V3) dataset, which is constructed from SST data in the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) (Smith et al., ~~2007~~2008; Xue et al., 2003). Monthly 10-m scalar wind speed data from 1950 to 2011 came from Wave and Anemometer-based Sea Surface Wind (WASWind) version 1.0.1 (Tokinaga and Xie, 2011), derived from ship observations in ICOADS and presented at a resolution of 4 × 4 degrees. Specific humidity data at 2-degree resolution was from ICOADS. Both wind speed and specific humidity databases have missing values in areas outside shipping routes, especially ~~in~~at high latitudes. ~~We used~~ Because Chiu et al. (2012) view oceanic evaporation, or sea surface latent heat flux (LHF) divided by the latent heat of vaporization (Lv), as a crucial factor of the global water and energy cycle, we used LHF data for 1950–2012 from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis (Kalnay et al., 1996) as a ~~robust~~fundamental proxy for oceanic evaporation~~ from the ocean~~. We also used data from the Japanese Re-Analysis 55 Years (JRA-55) (Kobayashi et al., 2015) and the European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year Reanalysis (ERA-40) (Uppala et al., 2005) ~~for comparison with~~ datasets and compared these datasets to the LHF data from NCEP/NCAR ~~to address~~and the moisture flux vector. Based on the comparison, we addressed possible reliability problems in moisture data from the pre-satellite era. Although there are some differences ~~among~~between these three databases, the differences do not significantly influence our conclusions. Our analysis primarily used ~~mainly~~ July-August-September (JAS) averages, corresponding to the Sahel region's rainy season~~ in the Sahel region~~.

Figure 1 shows the long-term ~~(1950–2012)~~ value of JAS average precipitation in northern Africa~~.~~ using PREC_L data. Our study area, defined as the region bounded by 10°N~~ and ~~-20°N and 8°W~~ and ~~-30°E, was chosen to avoid coastal influences on seasonal rainfall in the Sahel. The JAS has captured, by definition, the Sahel region rainy season between 200 to 600 mm per JAS per year and we used the PREC_L data for the smooth resolution of the data. Figure 2 shows the variation of JAS average rainfall in the study area from 1950 through 2012. Sahel rainfall ~~followed a decreasing trend~~decreased from the early 1960s to the mid-1980s, followed by an increasing trend for the rest of the study period. The driest year of the study period was 1984 (Munemoto and Tachibana, 2012~~).~~); we focused on that period to divide our dataset into two different periods, the decreasing and increasing periods. The mid-1980s mark a clear reversal in these multi-decadal trends. The signature of this trend shift is not sensitive to the definition of the study area (results not shown). Because the data were insufficient to analyze at least two cycles of multi-decadal variability, we focused on a phenomenon ("the trend shift") that might indicate a phase change.

~~In assessing~~To assess the degree to which trends in other climatic parameters~~ are~~ synchronized with the Sahel trend shift, we divided the time series of all datasets into the subperiods 1950–1984 and 1985–2012. We defined the trend in each subperiod as the angle of inclination, $\tan\theta$ ~~tanθ~~, of the time series, as calculated from the linear regression coefficient using the least squares method. We defined the strength of the trend shift, $\delta\tan\theta$ ~~δtanθ~~, as $\tan\theta_2 - \tan\theta_1$ ~~$\tan\theta_2 - \tan\theta_1$,~~, where the subscripts 1 and 2 denote the subperiods before and after 1984, respectively. To confirm that the trends of the two subperiods differed in sign, we added the condition $\tan\theta_1 \cdot \tan\theta_2 < 0$ ~~$\tan\theta_1 \cdot \tan\theta_2 < 0$.~~. We named a decreasing to increasing (increasing to decreasing) trend shift as a positive (negative) trend shift, i.e~~. $\delta\tan\theta > 0$ ($\delta\tan\theta < 0$~~., $\delta\tan\theta$ > 0 ($\delta\tan\theta$ < 0) and $\tan\theta_1 \cdot \tan\theta_2 < 0$ ~~$\tan\theta_1 \cdot \tan\theta_2 < 0$~~.

3 Results

3.1 Trend shifts of Sahel precipitation and ocean evaporation

The time series of the global JAS mean LHF ~~displays a decreasing trend~~decreased before the mid-1980s, followed by an increase (Fig. 2). Although this increase ceased after the mid-1990s, the turning point of the trend shift coincided with ~~that of~~ Sahel rainfall. Global annual mean LHF also had a similar trend shift to ~~those~~that of the JAS mean (~~Figure not shown~~Li et al., 2011). This synchrony suggests that, at the multi-decadal time scale, the variability of Sahel rainfall may be physically linked to the transport of the moisture ~~evaporated~~flux from the oceans. We also investigated global mean sensible heat flux, but found no significant trends during the study period.

The trend shift of LHF in the world ocean may be related to precipitation ~~in~~inside and outside the Sahel. The results of our investigation of this possibility are shown for both JAS and annual precipitation ~~in Fig. 3.~~of PREC_L in Figure 3a and 3b, respectively. The trend shift over the Sahel is stronger for annual precipitation than for JAS precipitation. The areas where the positive trend ~~shift~~shifts (from decreasing to increasing) in JAS precipitation ~~is~~are large are the Sahel, western coastal areas of South Asia, and equatorial South America (Fig. 3a).

For annual precipitation, the areas ~~of~~with positive trend ~~shift exceed~~shifts are more numerous than the areas ~~of~~with negative trend ~~shift~~shifts (Fig. 3b). Positive trend shifts are particularly strong in the Sahel, western coastal areas of South Asia, and southern Chile~~,~~ and less strong in Korea, Japan, the Philippines, Alaska, and northern Eurasia. Negative trend shifts are seen in South America, most of the ~~southern hemisphere~~SH, most of North America, and inland Eurasia~~. Areas of negative trend shift~~; these areas are weaker and narrower than the areas ~~of~~with a positive trend shift. These results indicate that a positive trend shift in precipitation occurred not only in the Sahel but elsewhere ~~on the globe.~~in the globe. Comparing the trend shifts of JAS precipitation of the PREC_L (Fig.3a), GPCC (Fig. 3c), and the University of Delaware (Fig.3d) datasets, similar land coverage was observed, with a correlation of 0.9; however, the University of Delaware (Fig. 3d) dataset showed a weaker signal over the same areas included in the PREC_L and GPCC datasets.

3.2 Global SST trend shift

Sahel rainfall is~~ known to be~~ related to nearby SST (Lough, 1986, Bader and Latif, 2003; Chung and Ramanathan, 2006) and remote SST (Folland et al., 1986; Janicot et al., 1996; Rowell, 2003; Fontaine et al., 2011; Munemoto and Tachibana, 2012; Diatta and Fink, 2014). Although there is not visible evidence of change, it is conceivable that the SST time series has a changing phase from 1984 using the SST over the northern hemisphere (NH) and SH. As demonstrated by Munemoto and Tachibana (2012), the NH SST became lower than that of the SH SST and described an opposite trend after 1984. Figure 4 shows that areas of positive trend shift in the JAS SST over the oceans are widespread in the NH, meaning that SST decreased until 1984 and then increased. Areas of negative trend shift are mostly in the SH, particularly the eastern tropical Pacific and the South Atlantic Ocean. The obvious contrast between hemispheres suggests that the change in JAS Sahel rainfall is somehow related to the hemispheric contrast in SST~~.~~; these results are consistent with the findings of Folland et al. ~~(1986) and Munemoto and Tachibana (2012).~~(1986) and Munemoto and Tachibana (2012). In addition, modeling and observational studies by Bader and Latif (2003) show that the Sahel region rainfall variability is linked with regional and global SST anomaly patterns, which include fluctuations in: the tropical Atlantic Ocean, as pointed out by Lamb (1978), Hastenrath, (1984), and Lamb and Peppler, (1992); the Pacific Ocean, as alluded by Janicot et al. (1996) and Rowell (2001); the Indian Ocean, as referred to by Palmer (1986) and Shinoda and Kawamura (1994); and the Mediterranean, as mentioned by Rowell (2003).

3.3 Trend shift of global ocean evaporation

~~Figure 5 shows the geographic distribution of the trend shift in mean JAS ocean evaporation, as signified by LHF. The areas of negative shift are much narrower than those of positive shift. A positive trend shift occupies the whole latitude range from 60°S to 40°N, except in the western South Pacific, northern and western Indian Ocean, and the Caribbean Sea. Areas where the trends changed sign between subperiods ($\tan\theta_1 \cdot \tan\theta_2 < 0$) cover most of the oceans, suggesting that the trend shift was genuine and worldwide.~~

The time change of the SST, i.e., SST trend, should be linearly related to the evaporation from the ocean provided that the ocean is treated as a slab. The time change of the evaporation, i.e., LHF trend, should thus be linearly related to the second-order differential of the SST. Here we simply compare between the two trend shifts, because the quality of the global dataset dose not resolve the second-order differential. Figure 5a and b show the JAS trend shift's geographic distribution of land water vapor flux and global ocean evaporation, as defined by LHF using NCEP and JRA-55 data, respectively. They both show a similar signs over the oceans, except at the coastline of western South America and the tropical Atlantic; one possible explanation is that the JRA-55 data are missing at least 10 years before 1984, which could capture the tropical Atlantic magnitude. When the subtropical SH Atlantic ocean is warmer (colder) than normal, greater (lesser) LHF production is observed, with a deeper surface coverage of the moisture flux transient through the western coast of the Sahel region, whereas the NCEP data show coverage transient through the eastern Sahel coast; similar results were found by Bader and Latif (2003). The NCEP and JRA-55 datasets captured a significant relation over the Sahel region, even though the JRA-55 evaporation rate increases at the western side of Sahel region and is negative in the eastern part. The relation of the tropical Pacific ocean, El Nino, and both the northern and southern Atlantic with the Sahel's rainfall variation, which was confirmed by Zhang et al. (2006), is observed in the JRA-55 data, but not the the NCEP/NCAR data.

3.4 Trend shifts of wind, humidity

Latent heat flux is determined by surface wind speed and the humidity deficit over the ocean. As displayed on Figure 6~~ shows~~, the trend shift of JAS surface scalar wind speeds over the ocean. This shift is positive over most of the SH, particularly in the eastern Pacific Ocean. Many of these positive areas match areas ~~of~~with positive LHF trend ~~shift in LHF~~shifts (Fig. 5). In the NH, the trend shift is positive over the subtropical central and eastern Pacific. Over the western subtropical North Atlantic ocean, the trend shift in the scalar wind is not in agreement with the trend shift in LHF~~. However~~; nevertheless, the overall similarity of Fig. 6 and Fig. 5 signifies that trend shifts in wind speed over the ocean partially account for the trend shift in LHF.

The trend shift in the JAS deficit of surface specific humidity, as determined from its saturated value at the local SST, is shown in Fig. 7. The geographic distribution of this positive trend shift is essentially global, similar to those of SST (Fig. 4) and LHF (Fig. 5) in the NH and the southern

Pacific Ocean. The positive trend shift of global evaporation from the ocean is therefore also partially explained by this trend shift.

Figure 8 shows a map of the JAS moisture flux trend shift using JRA-55. On this figure we can observe anticyclonic curvature from the eastern tropical Pacific toward tropical Atlantic; eastward flux from the tropical Atlantic to the Sahel region; the flux from Indian Ocean in about 40S trough the South Atlantic Ocean is also witnessed. This flux is further connected to the tropical Atlantic Ocean. Most importantly, this figure clearly highlights the key role the South of Indian Ocean and the East of the Pacific Ocean play in Sahel rainfall variation. In addition, a weaker transport from the North Atlantic through Mediterranean Ocean entrance to Libya is also observed, however this phenomenon is blocked by the local high pressure located in the Sahara desert.

4 Discussion and conclusion

Our study demonstrates an important synchrony between Sahel rainfall and global evaporation from oceans. The key point is that the shift in the trend of JAS Sahel rainfall from ~~decrease~~decreasing to ~~increase~~increasing (positive trend shift) ~~that~~ occurred in the mid-1980s and coincided with shifts in global-scale SST and evaporation from the oceans (Table 1). ~~The Sahel constitutes the world's largest area in which this trend shift occurred.~~ We found that the Sahel trend shift was synchronous with similar positive trend shifts in global oceanic evaporation (Fig. 2) and in land precipitation outside the Sahel, except in the Americas (Fig. 3). In detail, the trend shift in oceanic evaporation (as indicated by LHF) encompassed the SH and the subtropical NH, including the Pacific, Atlantic, and Indian Oceans (Fig. 5). Because increased oceanic evaporation strengthens global moisture transport toward the land, the synchronization of these trend shifts is physically plausible, and indeed the area of increased LHF exceeded the area of decreased LHF. Trend shifts also occurred in the mid-1980s in SST: the shift was negative (increase to decrease) in the SH and positive in the NH, giving rise to an interhemispheric contrast in SST (Fig. 4). The surface scalar wind over the ocean had a positive trend shift, mainly in the SH, that extended to the subtropical Pacific Ocean in the NH (Fig. 6). The humidity deficit displayed a positive trend shift in both hemispheres, particularly in the Pacific Ocean (Fig. 7). The strongest statement comes from the vector moisture flux, which clearly represents the path of the moisture flux from the eastern Pacific and South Indian Oceans through the tropical southern Atlantic to the western entrance of the Sahel region, and also the tropical northern Atlantic through northern Europe through Libya as an entrance that was, however, dissipated by the blocked high pressure in the Sahara region (Fig. 8). The eastern Pacific and South Indian Oceans are the areas where the positive trend shift of the latent heat flux is observed (Fig. 5)

From these results, we can ~~suggest possible processes~~assert that ~~connect~~the process that connects the trend shifts of the global oceans and Sahel rainfall (Fig. ~~8).~~9), which is the main reason for the positive trend shift in LHF, is the positive trend shift in scalar wind, particularly in the SH, because surface wind promotes evaporation from the ocean. ~~In general, high~~When SST is greater than normal, the atmosphere becomes unstable, leading to an interaction between convection and large-scale circulation that strengthens the convergence at the surface with a low wind speed at this center, generating a small amount of latent heat flux. LHF lowers the SST due to evaporative cooling~~.~~, which was also suggested by Wu et al. (2009) and Zhang et al. (1994). Therefore, the negative trend shift in SH SST~~ in the SH~~ may be an effect of the positive trend shift in the scalar wind. Giannini et al. (2003) and Zeng (2003) demonstrated that in the SH, when the gulf is warm, the Intertropical Convergence Zone (ITCZ) shifts south away from the Sahel, reducing the African monsoon that draws moist air into the Sahel, which means that long-term changes in Sahel rainfall are induced by changes in SST in the tropical Atlantic and Pacific oceans. The opposite way is that the advection of the magnitude of the moisture flux from the oceans toward the Sahel region forces the ITCZ to shift northward toward the Sahel region during the boreal summer. Although the linkages can be viewed as speculative and conceptual, the phenomenon could explain why both hemispheres are correlated positively, even though their SSTs are different.

In the NH, at latitudes lower than 40°N, the LHF trend shift tended to be positive, in synchrony with the positive SST trend shift. Because high SST in low latitudes generally promotes evaporation, the positive trend shift in LHF may be a consequence of the positive trend shift in SST~~.~~; the positive trend shift in the humidity deficit in the NH also supports this inference. Thus, the positive SST trend shift in the NH may be linked to the positive LHF trend shift. Although the trend shift in SST is positive in the NH and negative in the SH, hemispheric differences in the role of SST may result in a global positive trend shift in LHF.

Although our study offers an explanation for these global-scale trend shifts~~; however~~, the reason for the outsized signature of Sahel rainfall is still problematic. ~~Many previous studies have argued~~

~~for~~In line with our viewpoint, Pomposi et al. (2015) affirmed that "understanding of how the monsoon reacts to global SSTs remains incomplete because the system can be impacted by moisture availability locally and in the region as well as tropical atmospheric stability, both of which are influenced by ocean temperatures." In the past, the influence of SST in different remote sites was emphasized (Folland et al., 1986; Czaja and Frankignoul, 2002; Dijkstra, 2006; Ting et al., 2009), including in the Atlantic Ocean (Hu and Huang, 2006; Marullo et al., 2011; Martin et al., 2014), Pacific Ocean (Rowntree, 1972; Pan and Oort, 1983; Cayan and Peterson, 1989; Wallace et al., 1989), and Indian Ocean (Clemens et al., 1991; Ashok et al., 2001, 2003; Annamalai et al., ~~2005). Probably there is no single determining influence.~~2005). To identify how evaporation in these remote oceans drives Sahel rainfall, idealized atmospheric general circulation model studies will need to incorporate the anomalous SST patterns shown in this study. The processes underlying the trend shift of the ocean surface wind also must be identified. ~~Also of interest is how~~Additionally, it is noteworthy that the trend shift in oceanic evaporation might affect the global salinity distribution, and in turn the global thermohaline circulation. Remarkably, the SST-Sahel teleconnection seems to be stronger with the Indian Ocean (negative correlation) and Mediterranean index (positive correlation) in about 50% of the years of that era (Fontaine et al., 2011), which led us to conclude that the resemblance between global trends and trends in the Sahel makes it difficult to attribute changes in the Sahel to only a single teleconnection. Largely, the horizontal transfer of heat flux from oceans to the Sahel region through precipitation variability (or opposite) has been highlighted.

Furthermore, our experiments confirm the hypothesis that the south Indian Ocean, east Pacific Ocean, and Atlantic Ocean significantly influence not only regional climate anomalies, as Bader and Latif (2003) suggested, but also the relationship between global changes in SSTs and the Sahel region's rainfall variability, as revealed by Folland et al. (1986). The conclusion, which one can draw from these various studies, is that the Sahel constitutes the world's largest area in which this trend shift occurred. Rainfall or dry conditions in the West African Sahel region can definitely be associated with the role of the global oceans.

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References

Annamalai, H., Liu, P., and Xie, S. P.: Southwest Indian Ocean SST Variability Its Local Effect and Remote Influence on Asian Monsoons, J. Climate, 18, 4150–4167, doi: 10.1175/JCLI3533.1, 2005.

Ashok, K., Guan, Z., and Yamagata, T.: Impact of the Indian Ocean dipole on the relationship between the Indian Monsoon rainfall and ENSO, Geophys. Res. Lett., 28, 4499–4502, doi:10.1029/2001GL013294, 2001.

Ashok, K., Guan, Z., and Yamagata, T.: Influence of the Indian Ocean Dipole on the Australian winter rainfall, Geophys. Res. Lett., 30, 1821-1825, doi:10.1029/2003GL017926, 2003.

Bader, J. and Latif, M.: The impact of decadal-scale Indian Ocean sea surface temperature anomalies on Sahelian rainfall and the North Atlantic Oscillation, Geophys. Res. Lett., 30, 2169-2172, doi:10. 1029/ 2003GL018426, 2003.

Baines, P. G., and Folland, C. K.: Evidence for rapid global climate shift across the late 1960s, J. Climate, 20, 2721 – 2744, doi:10.1175/ JCLI4177.1, 2007.

Cayan, D. R. and Peterson, D. H.: The Influence of North Pacific Atmospheric Circulation on Streamflow in the West, in Aspects of Climate Variability in the Pacific and the Western Americas, Geophys. Monogr., No. 55, Amer. Geophys. Union, 375–397, doi:10.1029/GM055p0375, 1989.

Chen, M., Xie, P., Janowiak, J. E., and Arkin, P. A.: Global Land Precipitation: A 50-yr Monthly Analysis Based on Gauge Observations, J. Hydrometeor., 3, 249-266, 2002.

Chiu L.S, Gao S. and Shie C-L: Oceanic Evaporation: Trends and Variability, p261, 2012.

Christensen, J.H., Hewitson, B., Busuioc, A., Chen, A., Gao, X. Held, I., Jones, R., Kolli, R. K., Kwon, W.-T., Laprise, R., Rueda, V. M., Mearns, L., Menéndez, C.G., Räisänen, J., Rinke, A., Sarr, A., and Whetton, P.: Regional Climate Projections. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2007.

Chung, C. E. and Ramanathan, V.: Weakening of North Indian SST Gradients and the Monsoon Rainfall in India and the Sahel, J. Climate, 19, 2036–2045, doi:10.1175/JCLI3820.1, 2006.

Clemens, S., Prell, W., Murray, D., Shimmield, G., and Weedon, G.: Forcing mechanisms of the Indian Ocean monsoon. Nature, 353, 720-725, doi:10.1038/353720a0, 1991.

Czaja, A. and Frankignoul, C.: Observed Impact of Atlantic SST Anomalies on the North Atlantic Oscillation, J. Climate, 15, 606–623, doi:10.1029/2004JD005676, 2002.

Dai, A.: Drought under global warming: a review, WIREs Climate Change, 2, 45-65, doi:10.1002/wcc.81, 2011.

Delworth, T. L., Manabe, S., and Stouffer, R. J.: Interdecadal variations of the thermohaline circulation in a coupled ocean-atmosphere model, J. Climate, 6, 1993 – 2010, doi:10.1175/1520-0442(1993)006<1993:IVOTTC>2.0.CO;2, 1993.

Diatta, S. and Fink, A. H.: Statistical relationship between remote climate indices and West African monsoon variability, Int. J. Climatol., 34-12, 3348-3367, doi:10.1002/joc.3912, 2014.

Dijkstra, H. A.: Interaction of SST Modes in the North Atlantic Ocean, J. Phys. Oceanogr., 36, 286–299, doi:10.1175/JPO2851.1, 2006.

Folland, C. K, Palmer, T. N., and Parker, D. E.: Sahel rainfall and worldwide sea temperatures, 1901-85, Nature, 320, 602-607, doi:10.1038/320602a0, 1986.

Fontaine, B., Gaetani, M., Ullmann, A., and Roucou, P.: Time evolution of observed July–September sea surface temperature-Sahel climate teleconnection with removed quasi-global effect (1900–2008), J. Geophys. Res., 116, D04105, doi:10.1029/2010JD014843, 2011.

Giannini, A., Saravanan, R., and Chang, P.: Oceanic forcing of Sahel rainfall on annually to interdecadal time scales, Science, 302, 1027–1030, doi:10.1126/science.1089357, 2003.

Hagos, S. M. and Cook, K. H.: Ocean Warming and Late-Twentieth-Century Sahel Drought and Recovery, J. Climate, 21, 3797-3814, doi:10.1175/2008JCLI2055.1, 2008.

Hastenrath, S.: Interannual Variability and Annual Cycle: Mechanisms of Circulation and Climate in the Tropical Atlantic Sector, Mon. Weather Rev., 112, 1097-1107, doi:10.1175/1520-0493(1984)112<1097:IVAACM>2.0.CO;2, 1984.

Hoerling, M., J. Hurrell, Eischeid, J. and Phillips, A.: Detection and attribution of 20th century northern and southern African rainfall change, 19, 3989-4008, J. Climate, 2006.

Hu, Z. Z. and Huang, B.: Physical Processes Associated with the Tropical Atlantic SST Meridional Gradient, J. Climate, 19, 5500–5518, doi:10.1175/JCLI3923.1, 2006.

Hulme M.: Rainfall changes in Africa: 1931–1960 to 1961–1990. Int. J. Climatol. 12: 685–699, 1992.

Janicot, S., Moron, V., and Fontaine, B.: Sahel droughts and ENSO dynamics, Geophys. Res. Lett., 23, 515–518, doi:10.1029/96GL00246, 1996.

Kalnay E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Cheillab, M., Ebsuzaki, W., Higgins, W., Janowiak, J., Mo, K. C., Ropelewski, C., Wang, J., Leetma, A., Reynolds, P., Jenne, R., and Joseph, D.: The NCEP/NCAP 40-year reanalysis project, B. Am. Meteorol. Soc., 77, 437-470, 1996.

Kobayashi, S., Ota, Y., Harada, Y., Ebita, A., Moriya, M., Onoda, H., Onogi, K., Kamahori, H., Kobayashi, C., Endo, H., Miyaoka, K., and Takahashi, K.: The JRA-55 Reanalysis: General Specifications and Basic Characteristics, J. Meteorol. Soc. Jpn, 93(1),, 5-48, doi:10.2151/jmsj.2015-001, 2015.

Lamb, P. J., and R. A. Peppler: Further Case Studies of Tropical Atlantic Surface Atmospheric and Oceanic Patterns Associated with Sub-Saharan Drought, J. Climate, 5, 476-488, doi:10.1175/1520-0442(1992)005<0476:FCSOTA>2.0.CO;2, 1992.

Lamb, P. J.: Large-scale Tropical Atlantic surface circulation patterns associated with Subsaharan weather anomalies. Tellus, 30, 240-251, 1978.

Li, G., B. Ren, J. Zheng, and C. Yang: Trend singular value decomposition analysis and its application to the global ocean surface latent heat flux and SST anomalies, J. Climate, doi:10.1175/2010JCLI3743.1, 2011.

Lough, J. M.: Tropical Atlantic Sea Surface Temperatures and Rainfall Variations in Subsaharan Africa, Mon. Weather. Rev., 114, 561–570, doi:10.1175/1520-0493(1986)114<0561:TASSTA>2.0.CO;2, 1986.

Lu, J., and T. Delworth: Oceanic forcing of the late 20th century Sahel drought. Geophys. Res. Lett., 32, L22706, doi:10.1029/2005GL023316, 2005.

Martin, E. R., Thorncroft, C., and Booth, B. B.: The Multidecadal Atlantic SST—Sahel Rainfall Teleconnection in CMIP5 Simulations, J. Climate, 27, 784–806, doi:10.1175/JCLI-D-13-00242.1, 2014.

Marullo, S., Artale, V., and Santoleri, R.: The SST Multidecadal Variability in the Atlantic–Mediterranean Region and Its Relation to AMO, J. Climate, 24, 4385–4401, doi:10.1175/2011JCLI3884.1, 2011.

Munemoto, M. and Tachibana, Y.: The recent trend of increasing precipitation in Sahel and the associated inter-hemispheric dipole of global SST, Int. J. Climatol., 32, 1346–1353, doi:10.1002/joc.2356, 2012.

Omotosho, J. B.: Pre-rainy season moisture build-up and storm precipitation delivery in the West African Sahel. Int. J. Climatol., 28 937–946, 2008.

Palmer, T. N.: Influence of the Atlantic, Pacific and Indian Oceans on Sahel rainfall, Nature, 322, 251-253, doi:10.1038/322251a0, 1986.

Pan, Y. H. and Oort, A. H.: Global Climate Variations Connected with Sea Surface Temperature Anomalies in the Eastern Equatorial Pacific Ocean for the 1958–73 Period, Mon. Weather. Rev., 111, 1244–1258, doi:10.1175/1520-0493(1983)111<1244:GCVCWS>2.0.CO;2, 1983.

Rowell, D. P.: The Impact of Mediterranean SSTs on the Sahelian Rainfall Season, J. Climate, 16, 849–862, doi:10.1175/1520-0442(2003)016<0849:TIOMSO>2.0.CO;2, 2003.

Rowell, D. P.: Teleconnections between the tropical Pacific and the Sahel. Q. J. R. Meteorol. Soc., 127, 1683–1706, 2001.

Rowntree, P. R.: The influence of tropical east Pacific Ocean temperatures on the atmosphere, Q. J. ~~Roy. Meteor~~R. Meteorol. Soc., 98, 290–321, doi:10.1002/qj.49709841605, 1972.

Schneider, U., Becker, A., Finger, P., Meyer-Christoffer, A., Rudolf, B., and Ziese, M.: GPCC Full Data Reanalysis Version 6.0 at 2.5°: Monthly Land-Surface Precipitation from Rain-Gauges built on GTS-based and Historic Data, doi: 10.5676/DWD_GPCC/FD_M_V7_250, 2011.

Shinoda, M., and Kawamura, R.: Tropical rainbelt, circulation, and sea surface temperatures associated with the Sahelian rainfall trend. J. Meteor. Soc. Japan, 72, 341-357, 1994.

Smith, T. M., Reynolds, R. W., Peterson, T. C., and Lawrimore, J.: Improvements to NOAA's Historical Merged Land-Ocean Surface Temperature Analysis (1880-2006), J. Climate, 21, 2283–2296, 2008.

Stott, P. A., Gillett, N. P., Hegerl, G. C., Karoly, D. J., Stone, D. A., Zhang, X., and Zwiers, F.: Detection and attribution of climate change: A regional perspective, Wiley Interdiscip. Rev. Clim. Change, 1, 192-211, 2010.

Ting, M., Kushnir, Y., Seager, R., and Li, C.: Forced and Internal Twentieth-Century SST Trends in the North Atlantic, J. Climate, 22, 1469–1481, doi:10.1175/2008JCLI2561.1, 2009.

Tippett, M., and Giannini, A.: Potentially predictable components of African summer rainfall in an SST-forced GCM simulation, J. Climate, 19, 3133–3144, 2006.

Tokinaga, H. and Xie, S. P.: Wave and Anemometer-based Sea Surface Wind (WASWind) for Climate Change Analysis, J. Climate, 24, 267-285, doi:10.1175/2010JCLI3789.1, 2011.

Uppala and co-authors : The ERA-40 re-analysis, Q. J. R. Meteorol. Soc., 131, 2961–3012, doi:10.1256/qj.04.176, 2005.

Wallace, J. M., Mitchell, T. P., and Deser, C.: The Influence of Sea-Surface Temperature on Surface Wind in the Eastern Equatorial Pacific: Seasonal and Interannual Variability, J. Climate, 2, 1492–1499, doi:10.1175/1520-0442(1989)002<1492:TIOSST>2.0.CO;2, 1989.

Wolter, K.: Modes of tropical circulation, Southern Oscillation, and Sahel rainfall anomalies, J. Climate, 2, 149-172, doi:10.1175/1520-0442(1989)002<0149:MOTCSO>2.0.CO;2, 1989.

Wu R., Kirtman, B. P., and Pegion, K.: Surface latent heat flux and its relationship with sea surface temperature in the National Centers for Environmental Prediction Climate Forecast System simulation and retrospective forecasts, Geophys. Res. Lett., 34, L17712, doi:10.1029/2007GL030751, 2009.

Xue, Y., Smith, T. M., and Reynolds, R. W.: Interdecadal changes of 30-yr SST normals during 1871-2000, J. Climate, 16, 1601-1612, doi:10.1175/1520-0442-16.10.1601, 2003.

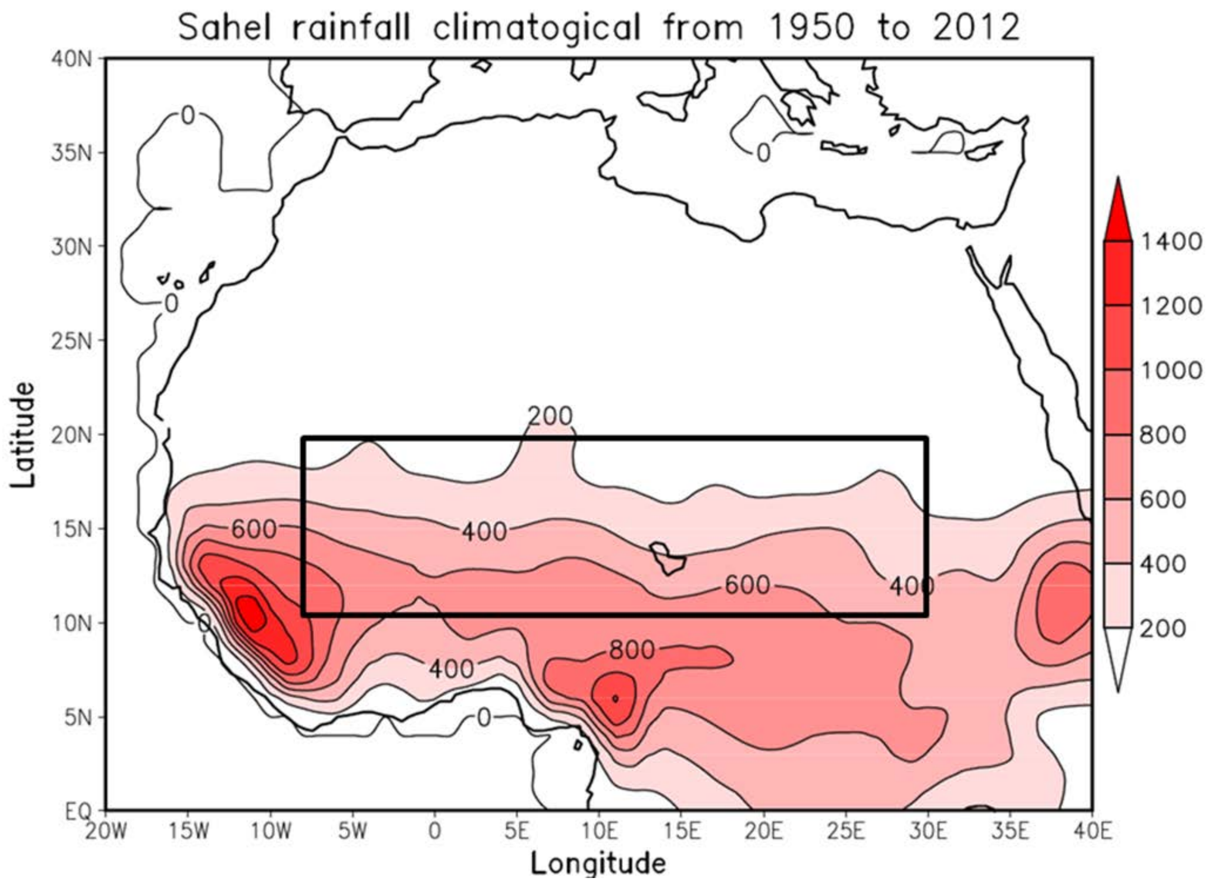
Zhang, R., and Delworth, T. L.: Impact of Atlantic multidecadal oscillations on India/Sahel rainfall and Atlantic hurricanes, Geophys. Res. Lett., 33, L17712, doi:10.1029/2006GL026267, 2006.

Zeng, N.: Drought in the Sahel, Science, 302, 999–1000, 2003.

Zhang G.,J, and Mcphaden M. J.: The relationship between sea surface temperature and latent heat flux in the equatorial Pacific, J. Climate, 8(3), 589–605, 1995.

Table 1. Summary of Results for JAS Meteorological Parameters. "Positive" indicates that a shift from decrease to increase occurred during 1950 to 2012; "negative" indicates a shift from increase to decrease.

	Sahel rain	SST	LHF	Wind	Humidity deficit
Northern hemisphere	Positive	Positive	Positive	Positive (tropical Pacific)	Positive
Southern hemisphere		Negative	Positive	Positive	Positive (Pacific)


Sahel rainfall climatogical from 1950 to 2012
Latitude
Longitude
40N
35N
30N
25N
20N
15N
10N
5N
EQ
20W
15W
10W
5W
0
5E
10E
15E
20E
25E
30E
35E
40E
1400
1200
1000
800
600
400
200
0
200
400
600
800

~~Figure Captions~~

~~Figure~~

Fig.1~~. Long-term (1950–2012)~~ Climatological JAS mean ~~summer (JAS)~~ of North Africa region rainfall ~~in northern Africa.~~ averaged from 1950 to 2012. The ~~study~~ area defined as the Sahel region is ~~outlined in black.~~in the rectangle between latitude 10-20°N and longitude 8°W-30°E. The unit is mm.

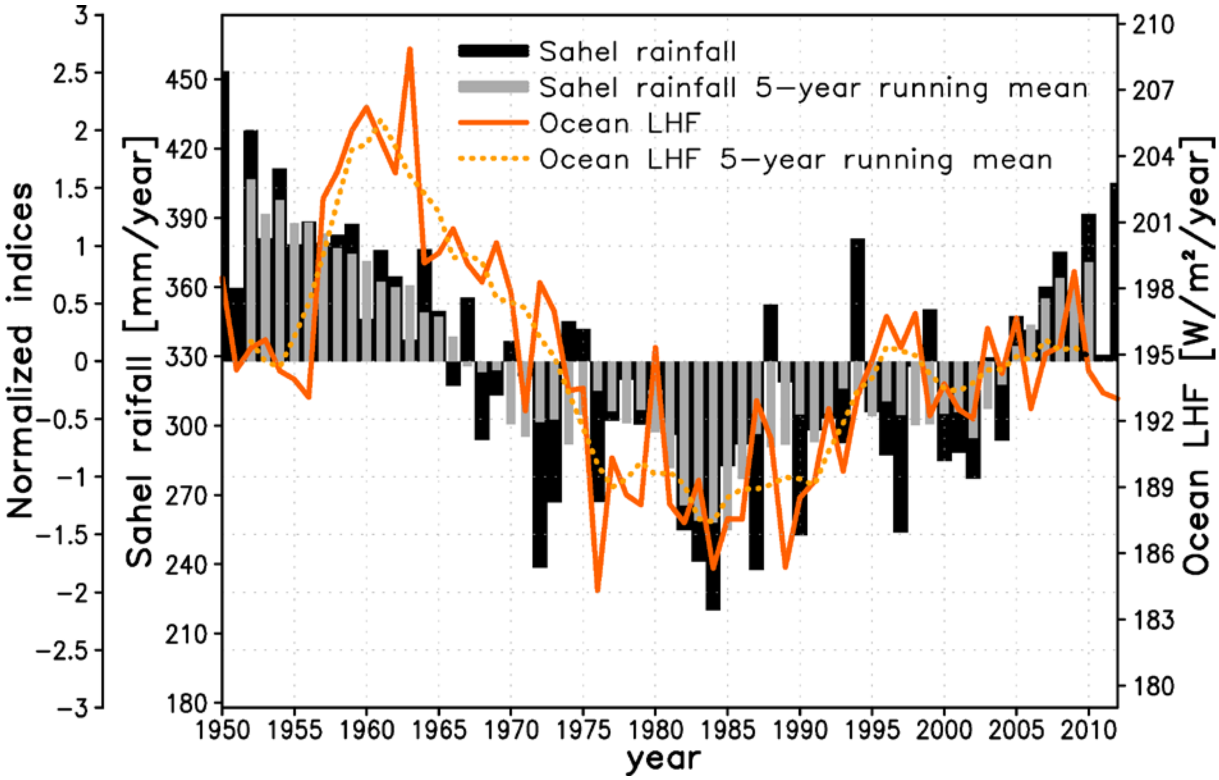
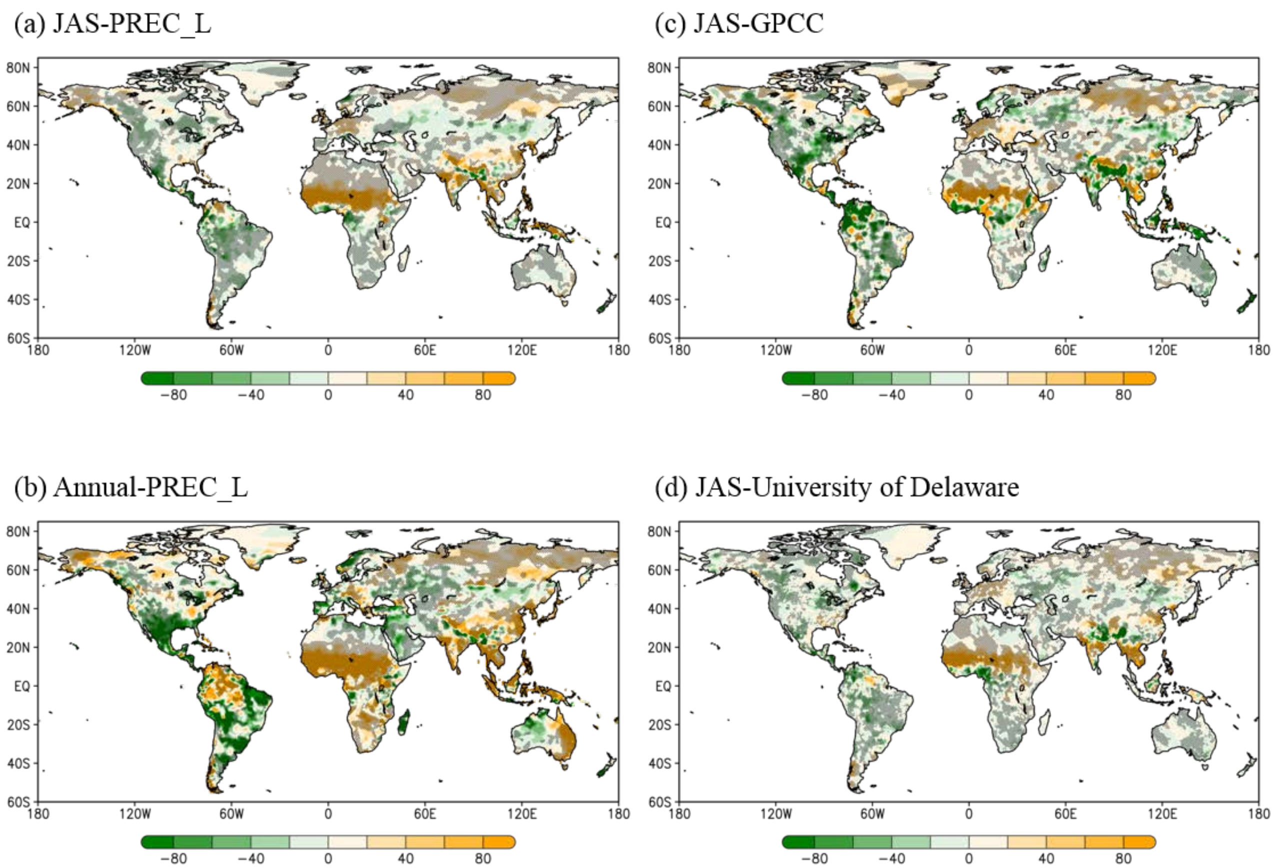


Figure 2. Time series of JAS Sahel rainfall (mm) and mean LHF (~~Wm~~W m^{-2}) from oceans from 1950 to 2012.



(a) JAS-PREC_L
(c) JAS-GPCC
(b) Annual-PREC_L
(d) JAS-University of Delaware
80N
60N
40N
20N
EQ
20S
40S
60S
180
120W
60W
0
60E
120E
180
−80
−40
0
40
80

Figure 3. Global maps of the trend shift for (a) JAS precipitation PREC_L (mm 10years^{-1}~~) and~~), (b) annual precipitation~~.~~, (c) JAS precipitation GPCC and (d) JAS precipitation University of Delaware. Shading denotes $\delta \tan\theta$ ~~δtanθ~~. Hatching represents areas where trends changed sign between the two parts of the study period ($\tan\theta_1 \cdot \tan\theta_2 < 0$ ~~$\tan\theta_1 \cdot \tan\theta_2 < 0$~~).

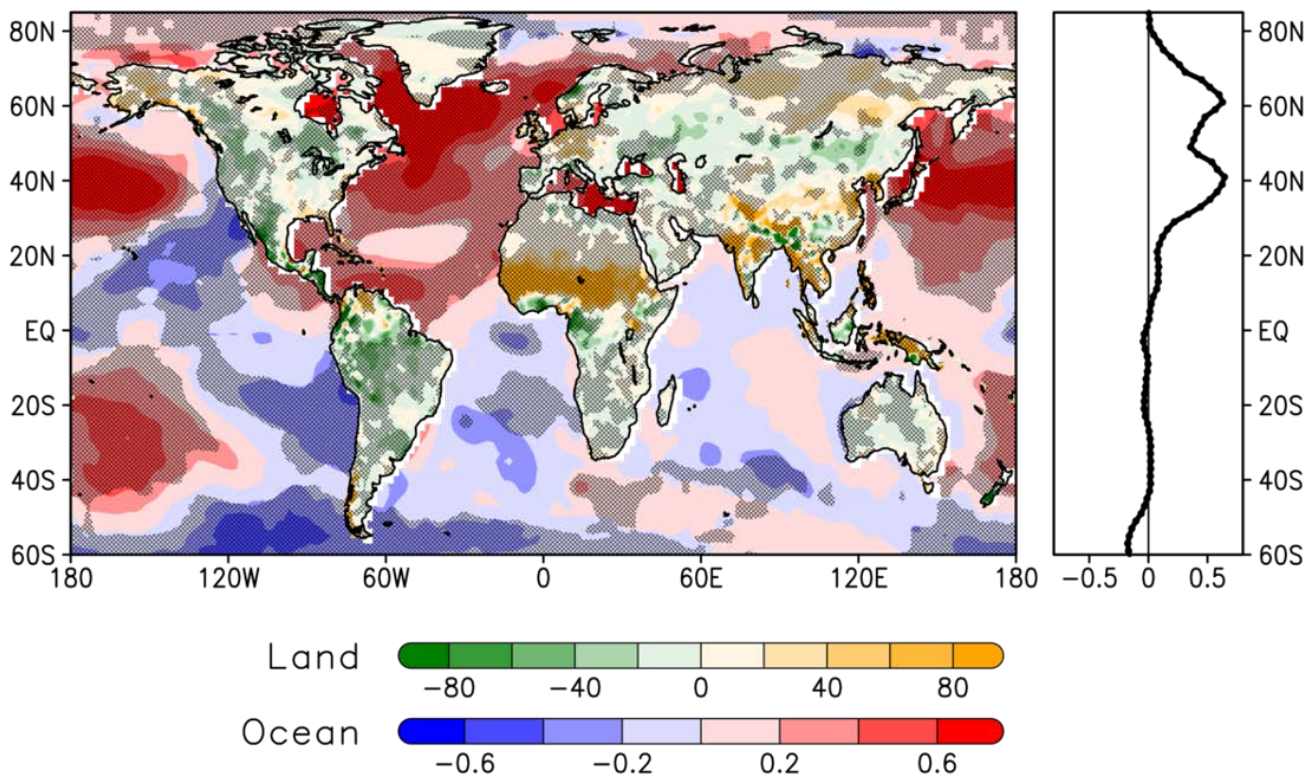
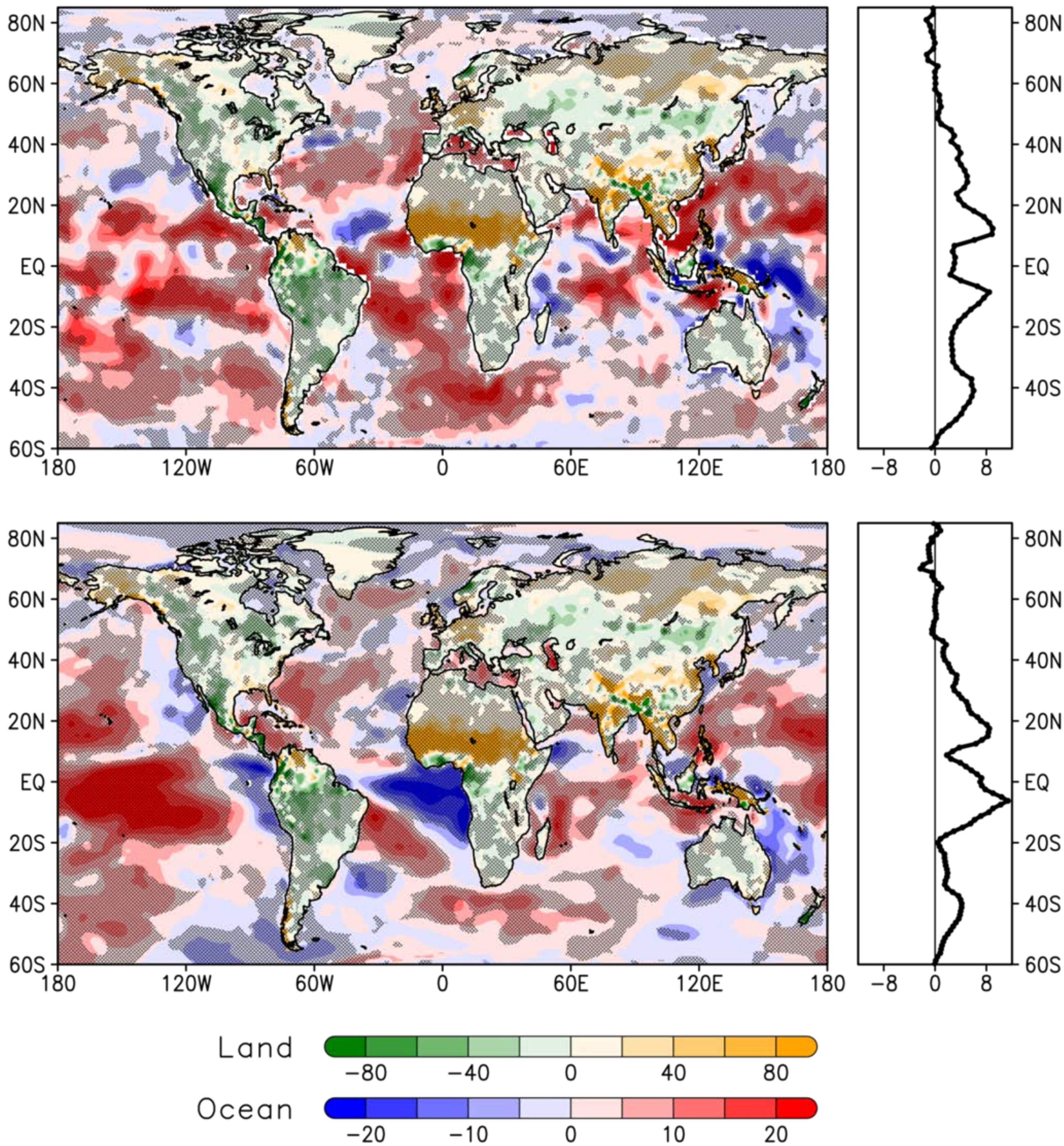


Figure 4. (Left) Trend shifts in SST (K/10years~~-1~~) and (Right) latitude profile of its zonal mean. ~~Land areas display trend shifts in JAS precipitation from Fig. 3a.~~

~~Figure 5. (Left) Trend shifts in latent heat flux (Wm^{-2} 10years^{-1}) and (Right) latitude profile of its zonal mean.~~ Land areas display trend shifts in JAS precipitation from Fig. 3a. Hatching represents areas where trends changed sign between the two parts of the study period ($\tan\theta_1 \cdot \tan\theta_2 < 0$).



80N
60N
40N
20N
EQ
20S
40S
60S
180
120W
60W
0
60E
120E
180
−8
0
8
Land
−80
−40
0
40
80
Ocean
−20
−10
0
10
20

Figure 5. Global maps of the LHF trend shift over the oceans for (a) JAS-NCEP (W m^{-2}/10years) and (b)JAS-JRA55. Land areas display trend shifts in JAS precipitation from Fig. 3a. Shading denotes $\delta \tan\theta$. Hatching represents areas where trends changed sign between the two parts of the study period ($\tan\theta_1 \cdot \tan\theta_2 < 0$).

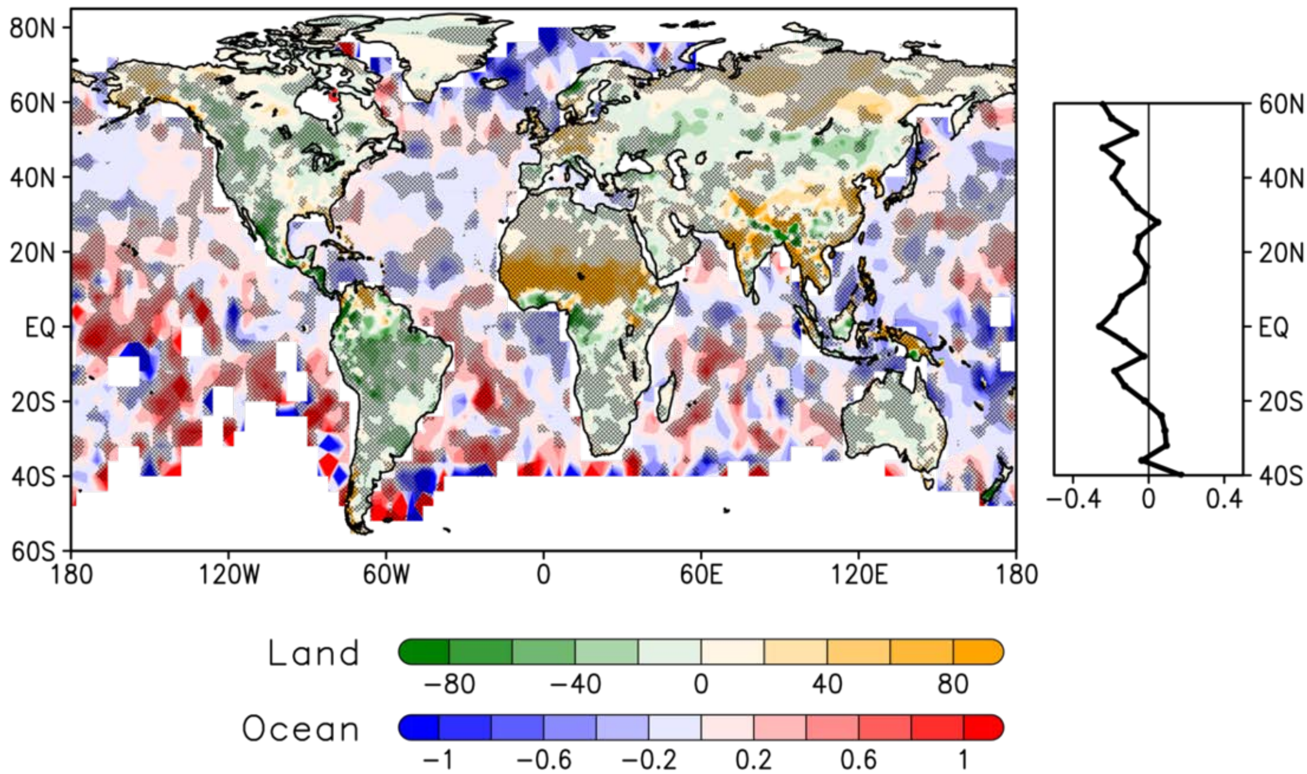
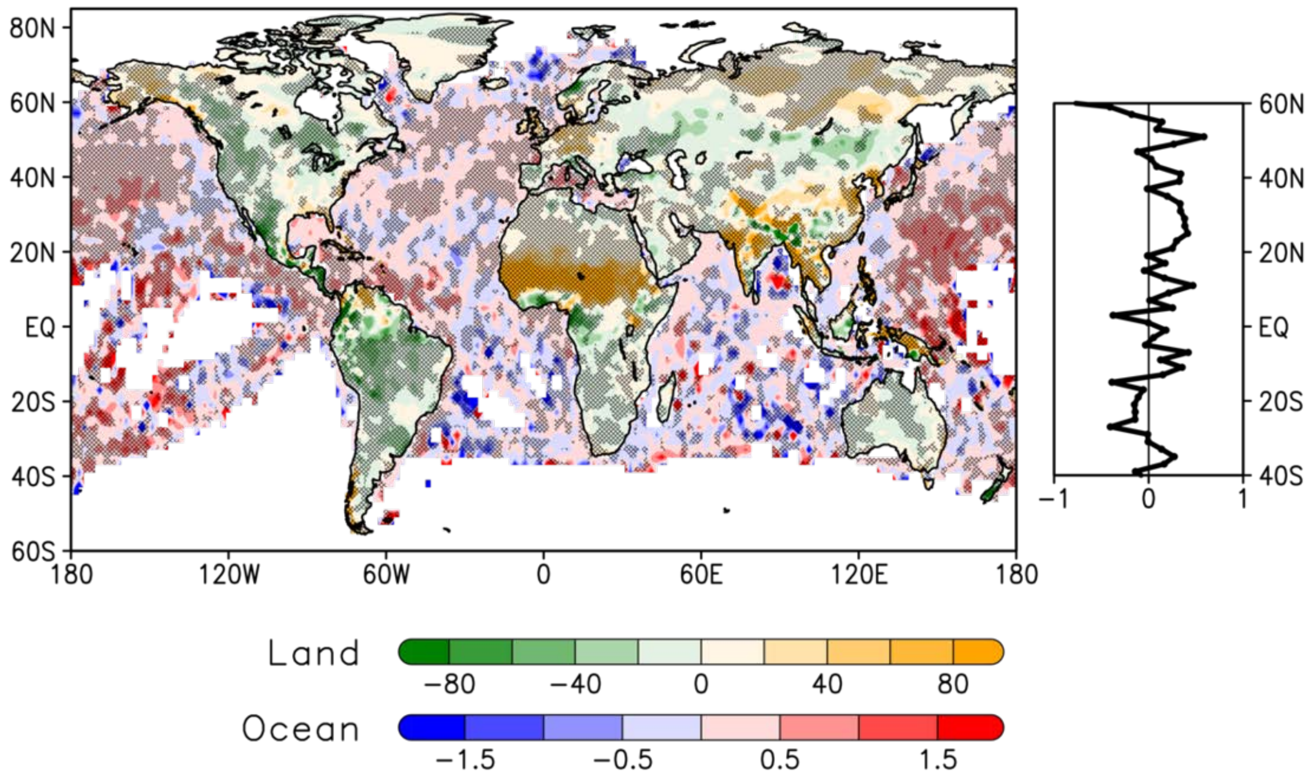
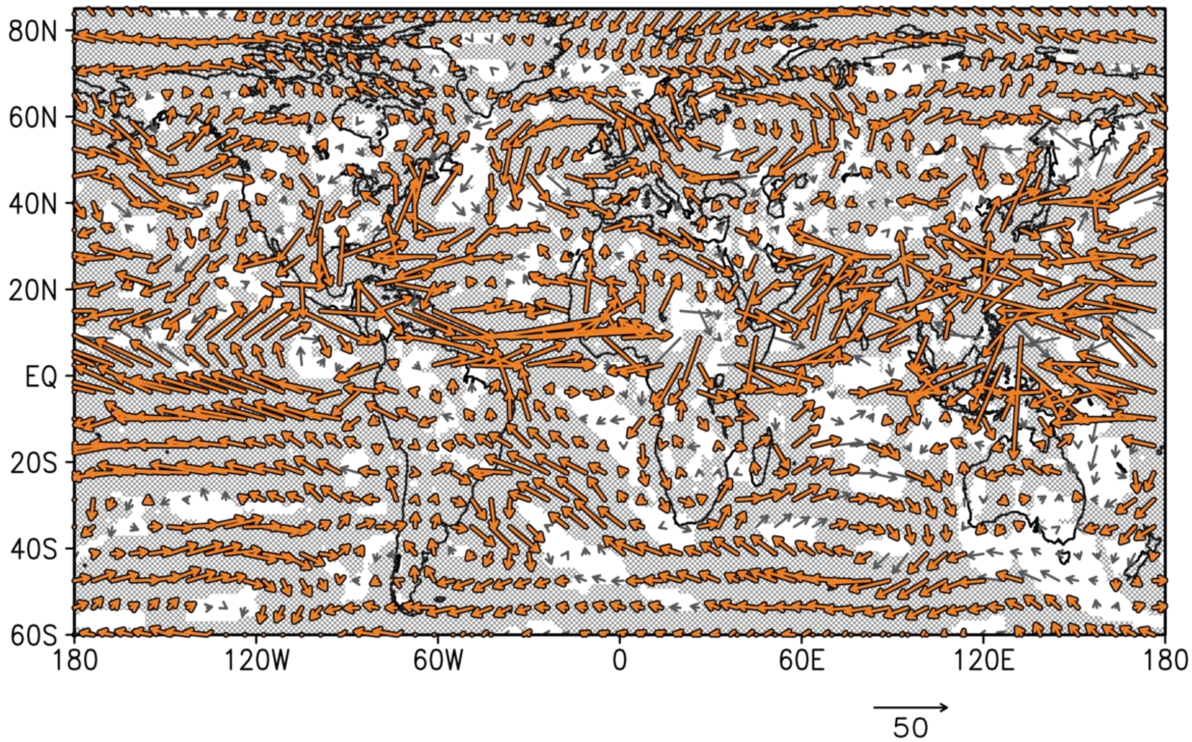


Figure 6. (Left) Trend shifts in scalar wind speed over the ocean (~~ms~~m s^{-1}/10years~~$^{-1}$~~) and (Right) latitude profile of its zonal mean. Land areas display trend shifts in JAS precipitation from Fig. 3a. Hatching represents areas where trends changed sign between the two parts of the study period ($\tan\theta_1 \cdot \tan\theta_2 < 0$).


80N
60N
40N
20N
EQ
20S
40S
60S
180
120W
60W
0
60E
120E
180
60N
40N
20N
EQ
20S
40S
−1
0
1
Land
−80
−40
0
40
80
Ocean
−1.5
−0.5
0.5
1.5

531

Figure 7. (Left) Trend shifts in the humidity deficit (gkg kg^{-1}/10years^{-1}) over the ocean and (Right) latitude profile of its zonal mean. Land areas display trend shifts in JAS precipitation from Fig. 3a. Hatching represents areas where trends changed sign between the two parts of the study period ($\tan\theta_1 \cdot \tan\theta_2 < 0$).



~~Figure 8.~~

Figure 8. Trend shift vector map of moisture flux using JRA-55 (kg m^{-1} s^{-1}/10years, 1958-2014: JAS). Orange bold vector and hatching represent areas where northward or eastward moisture flux trends changed sign between the two parts of the study period ($\tan\theta_1 \cdot \tan\theta_2 < 0$).

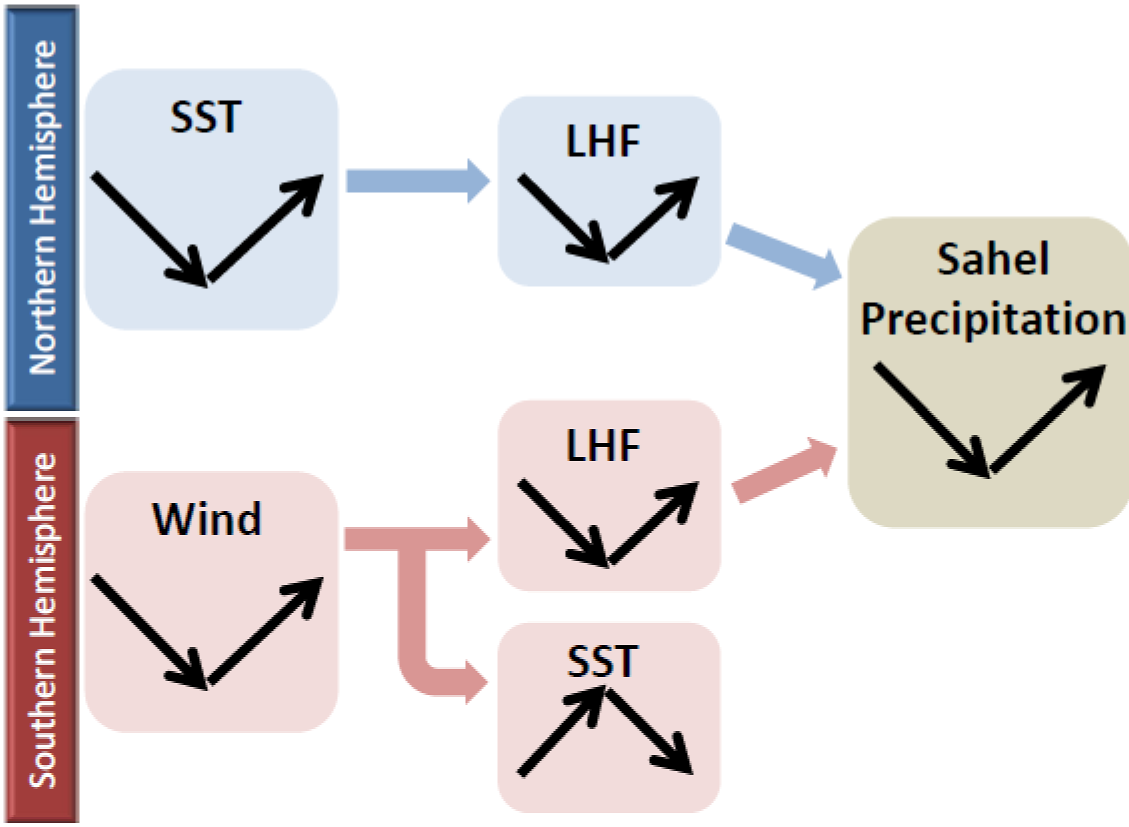


Figure 9. Schematic diagram of possible processes linking Sahel precipitation and the global ocean. The arrows represent increases or decreases in a parameter during 1950–1984 and 1985–2012.