

Interactive comment on “Comparison of simulated and reconstructed variations in East African hydroclimate over the last millennium” by F. Klein et al.

F. Klein et al.

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- [In blue: referees' comments](#)
- In black: our answers
- *In black italic: what we propose to add in the text*

The manuscript presents a comparative analysis of proxy records representative of hydroclimate in Eastern Africa and corresponding time series from climate simulations over the past millennium. After discussing the caveats due model spatial resolution and spatial homogeneity of precipitation this region, that authors reach the main conclusion that most of the hydroclimate variability in this region is probably caused by

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internal process and that the influence of external forcing seems to be very limited, in agreement with other studies that have pointed out the importance of internal variability in hydroclimate other parts of the world. Another important conclusion is that the different models do not agree in simulating the links between hydroclimate and sea-surface-temperatures. I think the research question is important and opens up further questions, as for instance the reasons why models diverge when simulating the SST-hydroclimate link which also leads to the question of the origin of hydroclimate variability itself and its connections to global patterns of climate variations like ENSO or the Indian Ocean dipole. My general impression of the manuscript is quite positive. The manuscript is rather long and, although at some stages the study falls short of reaching robust conclusions, I think it is a worthwhile contribution and opens up some lines of research for further studies. I liked the amount of manuscript space devoted to check the spatial representativity of the hydroclimate records, the skill of the models in simulating the two different precipitation annual cycles and the teleconnections to the large-scale SSTs, although I have a comment on this last point.

I have some comments on the manuscript that the authors may want to consider. Only two of them are general enough to possibly require some major changes in the manuscript, the rest being more more specific.

- I would like to start, however, underlying that the submitted version does not appear to have been thoroughly revised by the authors. Something seems to have gone awry regarding the blank spaces to separate words, and may words throughout the manuscript appear juxtaposed, at least in the pdf copy I downloaded. This has made the reading quite uncomfortable. This impression is confirmed by the acknowledgements to Flavio (?). I believe it is appropriate to acknowledge him by his full name.

We would like to apologize for that. Something went indeed awry when compiling our manuscript with the standard LaTeX template of Climate of the Past. We have noticed that the day after the submission and have then sent a corrected version of the manuscript, but it took some time to be updated. Anyway, we should have more

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thoroughly checked the initially submitted manuscript and we are sorry for the inconvenience.

- My main concern is the claim that precipitation, relative to evaporation, is the main factor driving hydroclimate variability. The authors compare the standard deviation of precipitation and evaporation in the model output and reach the conclusion that the former is much larger, with a few exceptions in the Challa/Naivasha region. However, this calculation is done at interannual timescales, as far as I can judge comparing the much larger magnitude of the standard deviations shown in Figure 6 than those shown in Figure 8, which are explicitly calculated at centennial timescales. If this is correct, I think this conclusion could be premature, since at longer timescales the variability of temperature would likely grow relative to the variability of precipitation, and thus also the role of evaporation could become more important. I think this should be checked because the authors base some of the further analysis on this conclusion, and because it is a quite relevant conclusion on its own right.

Thank you for pointing this out. You are right, in the submitted manuscript the comparison between the simulated standard deviation of precipitation and evaporation is computed using annually averaged results for the last millennium (850-2005 AD; Fig. 6 of the manuscript). One could indeed expect an increasing importance of temperature and thus of evaporation when using the results averaged over longer timescales. However, this is not the case in the models (Fig. 1 of this document). Using a smoothing window of 100 years, the differences between the standard deviation of precipitation and evaporation drop by a factor of about 10, but the relative amplitudes remain approximately the same to what is shown using annual results, meaning that precipitation still dominates on evaporation.

We propose to add the following sentence at the end of Section 4.2:

Moreover, also at timescales longer than annual, rainfall has a dominant role in explaining changes in P-E, since approximately the same picture is observed when smoothing

model results with a loess filter window of 100 years (not shown).

- Another point is related to the teleconnections between precipitation and sea-surface-temperature described in section 3.3. This section directly assumes that the SST is a direct driver of precipitation, but the text does not contain a justification for this assumption. Could it be that both SSTs and precipitation are driven by the atmospheric circulation? In this region, both may be coupled being part of some coupled mode of variability, but it is also possible that the atmosphere is driving both. This possibility is related to the main conclusion of the paper that the influence of external forcing is negligible, as the atmosphere circulation would be arguably less responsive to forcing than the SST.

You are right. Although the association between tropical Indian and Pacific Ocean SSTs and East African rainfall has been emphasized in numerous studies (see references in the introduction), only a few of them really focus on understanding the underlying mechanisms. Here, we observe that SSTs and precipitation are correlated. However, based on available climate model experiments we cannot say whether both variables are part of a coupled mode of variability, are dynamically linked independently of a mode, or are just correlated without any dynamical link. Answering this question would probably require additional simulations with sensitivity experiments, which is outside the scope of this study.

Nevertheless, it is instructive to test if models are able to reproduce observed correlations, whatever the cause of those correlations. We propose to explain that more explicitly in Section 3.3 of the revised version of the manuscript:

In addition to evaluation of the mean state, it is important to assess the ability of climate models to represent the observed regional patterns in the inter-annual variability of East African rainfall. Although it is not our goal here to study the mechanisms responsible for this simulated variability, it is illustrated by calculating the correlation between East African precipitation and tropical SSTs, which are considered a direct

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driver of precipitation over East Africa (e.g. Goddard and Graham, 1999; Ummenhofer et al., 2009).

We will also clearly state in Section 3.3 that these correlations do not necessarily imply dynamical links.

Particular points:

- The 1000-year time series representing hydroclimate variation in the Lake Challa region in Tierney et al. (2013) is the first principal component of composite variation in three moisture-balance proxies, namely a presumed indicator of catchment [precipitation]. It would be useful to quote the variance explained by this leading PC. Is it clearly over 30%, which would be the expected value if the three series were uncorrelated?

PC1 accounts for 40% of the variance in the 3 data time series, as mentioned in the supplementary materials of Tierney et al. (2013). This information will be added in Section 2.2 (Proxy-based hydroclimate reconstructions).

- pattern during an El Niño of ENSO. typo

This will be corrected.

- the series has been linearly standardized so that the maximum of the absolute values equals 1. This standardization is not really robust, as it depends on one single value: the maximum element in the series. The amplitude of the standardized series may therefore depend on an outlier.

Here, the outliers do not have an important impact on the amplitude of the standardized series since the raw time series are annually averaged and filtered before being standardized. We limited the amplitude of the time series between -1 and 1 mainly for aesthetic reasons. If we standardize by dividing the time series by their standard deviation instead of their maximum, the resulting figure is qualitatively the same (Fig. 2 of this document). We propose thus to keep the figure as in the submitted manuscript.

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- I really had to wrestle to understand Figure 9. First, I could not see the individual simulations of the CESM ensemble in panel upper row centre, apparently drawn with different shades of grey according to their distance to the median. I do not think it is necessary to show the distance to the median (what is the reason ?), and it quite messes up the figure. What would be the distance criterion anyway?

We wanted to show the information contained in all 10 ensemble members of CESM1 while having a clear picture. Showing all individual members makes the figure quite noisy (Fig. 3 a of this document), so our compromise was to draw the median of these ensemble members together with the range (Fig. 3 b of this document). The different shades of grey correspond to the number of ensemble members included between the median and the edges of the shades: for a given year, the furthest ensemble member (corresponding to the range) is thus drawn in the lightest grey, the second furthest in a bit darker grey, etc. We are sorry you could not discern between the different shades of grey and will make sure that the distinction between them is adequate in the revised version of this figure.

Second, I did not understand the blue shading. It apparently shows the $2 \times$ standard deviation derived boundaries from a control run, added to the median simulation (?). But it seems that the blue shading is not simply the median line with (constant) $2 \times$ sigma boundaries added. The blue-shaded area has a time evolution that is different to that of the median simulation.

The blue shading is indeed $2 \times$ standard deviation computed from the pre-industrial control runs, but around zero, as mentioned in the caption. The shading is thus drawn between $-2 \times$ standard deviation to $+2 \times$ standard deviation. It is not added to the median simulation. These values are constant through time.

Third, if the blue-shading indicates the standard deviation from control simulations, it is much smaller than the standard deviation from the forced simulation, so why is the line indicating the latter dashed?

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If you refer to the results from CESM1 in the Masoko/Malawi region, the standard deviation of the control run is indeed smaller than the standard deviation of the forced simulation (which is not the case for Challa/Naivasha). It has to be noted that in the case of CESM1, the standard deviation of the forced run shown is the mean of the standard deviation of each ensemble member, and not of the standard deviation of the median which would have prevented any valuable comparison with the standard deviation of the single control run.

The red line, which represents the mean of $2\times$ standard deviation of each forced run of CESM1 around zero, is dashed because it is significantly different from the same diagnostic computed from the control run, according to a F-test (5% level).

My impression is that this caption is not quite right. Maybe the blue shading indicates the within-ensemble standard deviation from the CESM ensemble (and so it is time-evolving as well) and not the standard deviation from a control run (constant). I think I see the point that the authors are trying to make in this panel. Perhaps the authors may want to consider just showing one or two simulations from the CESM ensemble if what they wish is to convey the amplitude of variations as compared to the other models. Showing the median is misleading (compared to other models), and showing the within-ensemble standard deviation (if this is what the blue-shading indicates) does not alleviate the problem.

Given the above information, we don't think that the caption is wrong, but we propose to modify it to be more explicit:

Figure 9: Simulated time series of P-E over the Challa/Naivasha and Masoko/Malawi regions throughout the last millennium (850-2005). Results are mean annual values smoothed using a loess filter with a window of 100 years, and are presented as anomalies with respect to the entire period. The horizontal red lines are displaced on both sides of the zero line at two times standard deviation of the smoothed time series. The horizontal blue lines also represent 2 standard deviations on both sides of zero

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but based on the time series from pre-industrial control simulations. The horizontal lines are dashed if the variance of the simulation with time-varying forcing (black line) is significantly different (F-test, considering a 5% level) from the variance of the simulation with fixed forcing; if not, it is solid. For the CESM1 model, the black curve is the median of the ten ensemble members, while the range is shown in grey shading. Within the grey area, the ranges excluding the furthest ensemble members above and below the median, the furthest two ensemble members above and below the median and the furthest four ensemble members above and below the median are drawn using increasingly darker shades of grey.

Also, to make the figure clearer, we propose to replace the blue-shaded area by two horizontal blue lines only, and to change the colour of the horizontal black lines to red, as in the Fig. 4 of this document.

[Interactive comment on Clim. Past Discuss.](#), doi:10.5194/cp-2015-194, 2016.

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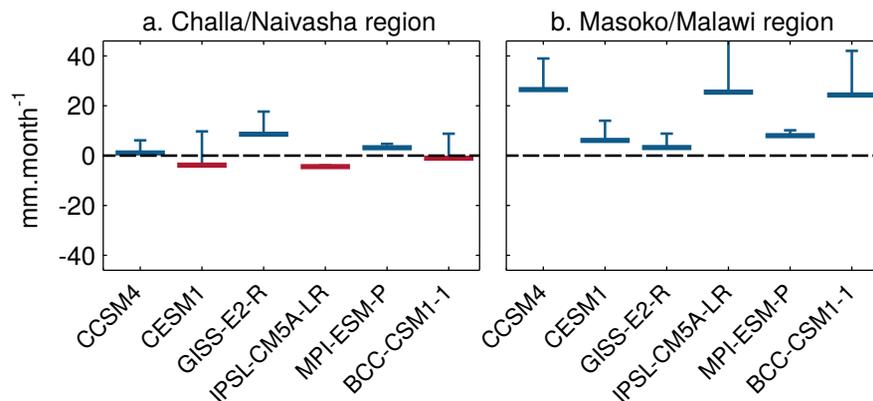


Figure 1 – Mean annual precipitation minus mean annual evaporation (horizontal bars), and standard deviation of annual precipitation minus the standard deviation of annual evaporation (vertical bars) using smoothed results with a window of 100 years. The period considered is the entire last millennium (850-2005). The differences between the standard deviation of precipitation and evaporation (vertical bars) are multiplied by 10.

Fig. 1.

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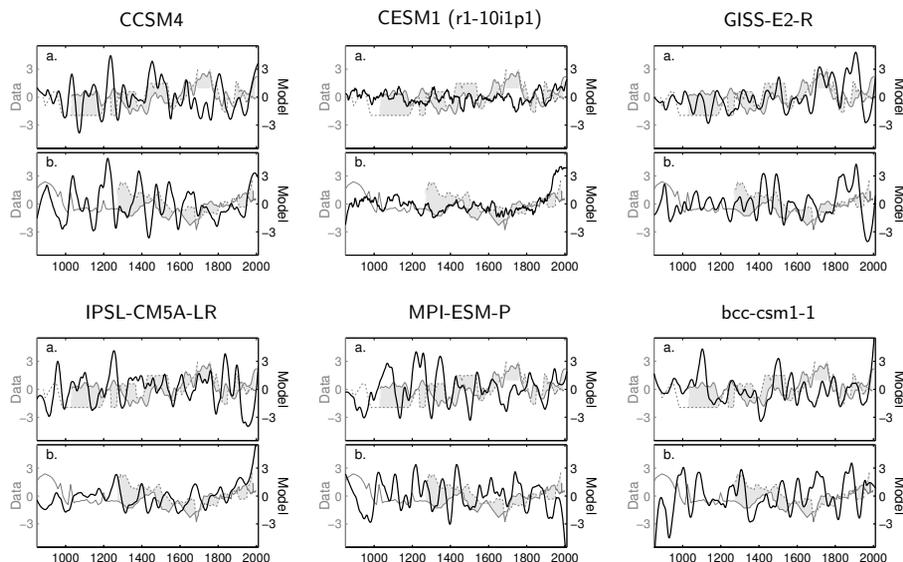


Figure 2 – Comparison between last-millennium time series of the reconstructions (in grey) and of P-E simulated by six GCMs (in black) averaged over the Challa/Naivasha region (a), with the Naivasha record shown as dashed line and the Challa record as solid line; and over the Masoko/Malawi region (b), with the Malawi record shown as dashed line and the Masoko record as solid line. In both regions, the area between the two records is shaded in light grey. Both proxy-based and simulated time series are presented as anomalies with respect to the whole period, and are standardized by being divided by their standard deviation. Ordinate axes are oriented such that wetter (drier) conditions point upwards (downwards). Model time series are annual mean values filtered using a loess method with a window of 100 years. For the CESM1 model, the black curve is the median of the ten ensemble members previously standardized and smoothed.

Fig. 2.

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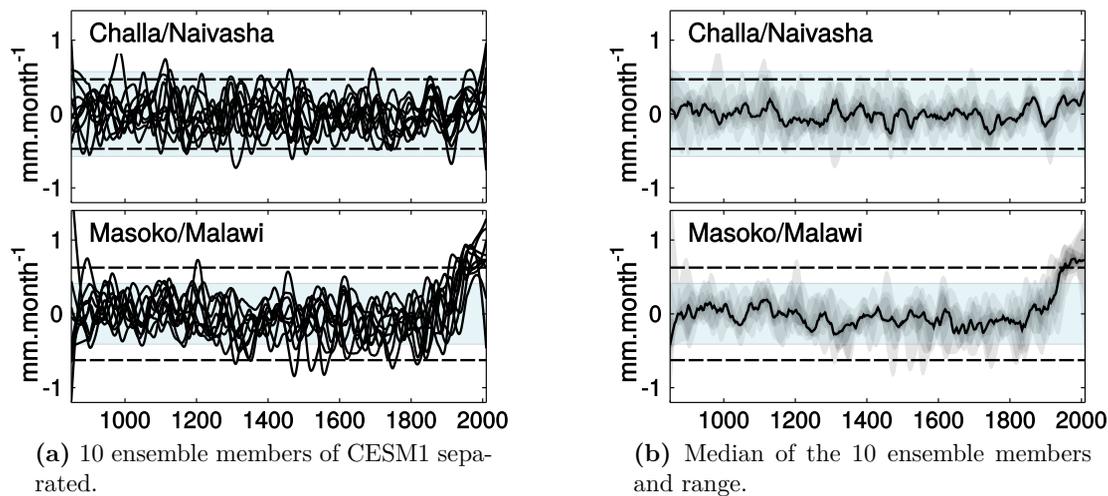


Figure 3

Fig. 3.

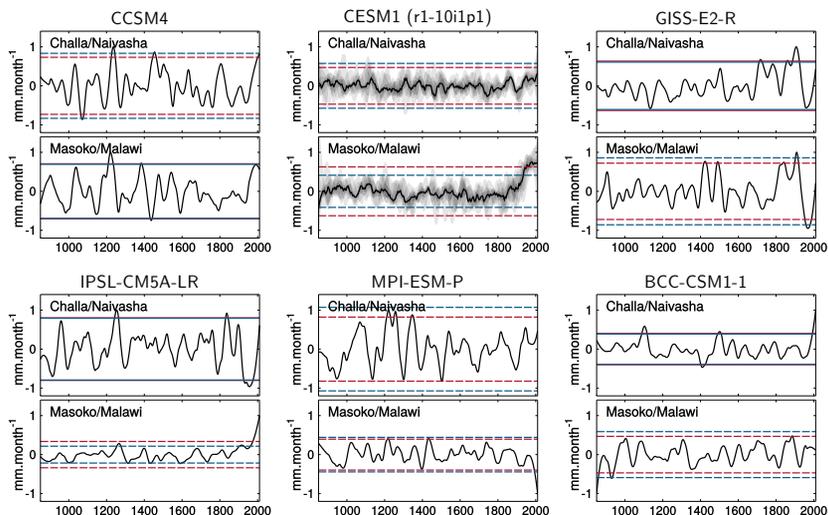


Figure 4 – Simulated time series of P-E over the Challa/Naivasha and Masoko/Malawi regions throughout the last millennium (850-2005). Results are mean annual values smoothed using a loess filter with a window of 100 years, and are presented as anomalies with respect to the entire period. The horizontal red lines are displaced on both sides of the zero line at two times standard deviation of the smoothed time series. The horizontal blue lines also represent 2 standard deviations on both sides of zero but based on the time series from pre-industrial control simulations. The horizontal lines are dashed if the variance of the simulation with time-varying forcing (black line) is significantly different (F-test, considering a 5% level) from the variance of the simulation with fixed forcing; if not, it is solid. For the CESM1 model, the black curve is the median of the ten ensemble members, while the range is shown in grey shading. Within the grey area, the ranges excluding the furthest ensemble members above and below the median, the furthest two ensemble members above and below the median and the furthest four ensemble members above and below the median are drawn using increasingly darker shades of grey.

Fig. 4.

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Summary: This study uses a paleoclimate model data comparison framework to analyze East African lake levels over the last millennium. GCMs struggle to represent the seasonal cycle of precipitation and teleconnections over East Africa. Nevertheless, the telconnections appear to be variable over the last millennium, and between fixed forcing

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and variable forcing simulations. For the Masoko/Malawi region, in particular, anthropogenic forcing appears to influence the teleconnections. On centennial timescales the variation in teleconnections are large for both regions and this is explained by changes to natural forcing. Despite a clear link between forcing and teleconnection changes in the models over the last millennium, there is no relationship between forcing and hydroclimate changes. By contrast, internal atmosphere-ocean variability is shown to be the dominant driver of simulated hydroclimate changes over East Africa, even on centennial timescales (although anthropogenic has driven consistent simulated changes in the Masoko/Malawi region over the most recent 150 years). The dominant role for internal atmosphere-ocean variability in driving hydroclimate changes can explain the mismatch between the time histories of hydroclimate over East Africa simulated by models and that reconstructed for the four lakes.

General Remarks: This represents an interesting and important contribution to our understanding of low-frequency hydroclimate variability over East Africa as simulated by models. My comments are largely minor although I do have three major concerns that I hope that the authors will consider addressing.

Major Concerns: 1. The manuscript, in general, is clear although I would strongly suggest revisiting the manuscript and editing for grammar and sentence structure.

We will check again the manuscript carefully and do our best to improve the grammar and sentence structure. It will eventually go through the copy editing process of *Climate of the Past*, which will help improve the language as well.

2. (Page 23, Line 6) “An interesting question is whether the forcing actually alters the dynamical link between East African rainfall and SSTs, or if it only masks it because of a different impact on continental rainfall and SSTs. Answering this question is out of the scope of this study, but it is of interest for the interpretation of records used for reconstructing phenomena like the IOD. Indeed, if dynamical relationships are not stable when considering different time scales, a record calibrated in observations of the

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recent period may not be representative of the studied phenomena over longer time scales.” This is very important and likely the most important conclusion of the paper, is there not some relatively simple way to approach this (specifically determining if the forcing actually alters the dynamical link between East African rainfall and SSTs, or if it only masks it because of a different impact on continental rainfall and SSTs)? I think it would really improve the contribution that this paper will make to our understanding of simulated and real-world East African rainfall. In particular, the CESM last millennium ensemble would seem to be well suited to answering this question given that the ten ensemble members can be used to robustly determine the impacts of forcing relative to internal variability.

Thank you for the suggestion, we agree that this is an important point. We can indeed determine the impact of the forcing on the teleconnections by comparing the average of the results of the 10 time-varying forcing experiments (r1-r10i1p1) with the results of the control simulation that fixes forcing to their pre-industrial values (Fig. 1 of this document).

We can see that the teleconnection patterns in the 'historical', 'past1000' and 'PI control' experiments of CESM1 are very similar. This is confirmed by the very small difference between 'historical' (simulation with the strongest forcing) and 'PI control' runs (lower row of Fig. 1 of this document). This means that the impact of forcing on teleconnection patterns is modest and that this pattern in CESM1 is dominated by internal variability. If we look in detail at the lower row of Fig. 1 of this document, we see that considering changes in forcing tends to dampen the teleconnections: the positive correlations get slightly less positive, and the negative correlations slightly less negative. This is interesting but the impact is, however, very small. Furthermore, this does not give any information about the mechanisms involved in the changes in the teleconnection patterns due to forcing, which would require new simulations with sensitivity experiments. Also, we can't consider these results as robust, since they are only based on a single model while most models show substantial differences in their

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representation of the teleconnections studied. Hence, we think that the above analysis does not add value to the core of the manuscript, and prefer not to include it.

3. When analyzing the reconstructions, Challa and Naivasha look very different, as do Malawi and Masoko. I found that the descriptions of common changes here were not consistent with what can be seen by eye in the figure. Perhaps there is a more quantitative way to approach this? Generally, I suggest that this section be revisited. If the reconstructions do not line up why might this be and what does this suggest for our interpretation of the model simulations?

We agree with the referee: although common features do occur between Challa and Naivasha (peak wetting around 1700 AD) and between Masoko and Malawi (dry conditions around 1700 AD), these records are different. We propose to rewrite Section 4.1 accordingly:

Notwithstanding chronological uncertainty, the Challa and Naivasha proxy records display clear differences during the first four centuries of the last millennium. In particular, the former shows roughly a drying trend while the opposite is recorded in the latter (Fig. 5). However, from around 1400 AD the general trends inferred from these two records are similar: both show relatively dry conditions followed by a wetting trend peaking between about 1700 and 1750 AD. After this peak, both hydroclimate reconstructions depict an abrupt transition towards a dry period in the early 19th century, followed by smaller-scale hydroclimate fluctuations at Naivasha and a clear wetting trend at Challa.

<Figure 5 of the manuscript>

Contrasting with Challa and Naivasha, lakes Masoko and Malawi both show a general drying trend culminating around 1700 AD, before an increase in humidity towards the present. However, (multi-) decadal hydroclimate changes overlying these long-term trends often strongly differ from one another in the two records.

The differences between the Challa and Naivasha reconstructions on the one hand and

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between the Masoko and Malawi reconstructions on the other can be viewed as a measure of the compound uncertainty of these proxy time series to represent the region's hydroclimate history. This may partly reflect real differences in the local hydroclimate history of these sites due to their different exposure to the principal seasonal moisture sources as affected by distance to the sea, topography etc. However, the most likely greatest source of time-series differences observed within each pair of records is due to the compound effects of i) dating uncertainty in these lake-based proxy records, ii) differences in hydrology and local catchment processes influencing a lake's (or its surrounding vegetation) sensitivity to climate, and/or iii) the fact that the used hydroclimate proxies have a specific and different relationship with temporal variation in our target of reconstruction, i.e. the climatic moisture balance. What is important here is that the differences between the two pairs of records are qualitatively more significant than those within each pair, to the extent that each pair is representative of a distinct hydroclimatic region (cf. Tierney et al., 2013). In the Challa/Naivasha region the main phase of the Little Ice Age equivalent period was wetter than average, and in the Masoko/Malawi region it was drier than average.

In the submitted manuscript, the simulated time series for Challa and Naivasha on the one hand and for Masoko and Malawi on the other are averaged over regions larger than the individual grid cells for those lakes. This is justified because according to climate models and recent observations (see Section 3.2) these sites are located in climatically homogeneous regions. In contrast, given the real differences between the reconstructions within each pair of sites, they are shown individually in our figures.

Specific Comments:

Abstract: "The bimodal seasonal cycle characterizing the Challa/Naivasha region, except that in the latter the relative magnitude of the two rainy seasons is less well captured." This language doesn't seem fully consistent with the results, it appears that the models generally struggle to reproduce the characteristics of the seasonal cycle at both locations.

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We agree with the referee, this sentence appears too optimistic. Although some models actually perform quite well at representing the observed seasonal cycle in Challa and Naivasha (Fig. 2 of the submitted manuscript and Table 1 of this document), there is a large spread among models as mentioned in Section 3.1.

Table 1. Pearson correlation coefficients between the observed and simulated seasonal cycle over the period 1979-2005.

	CCSM4	CESM1	GISS-E2-R	IPSL-CSM5A-LR	MPI-ESM-P	BCC-CSM1-I
Naivasha	0.17	0.43	0.68	0.59	0.47	0.49
Challa	0.37	0.65	0.57	0.92	0.50	0.70
Masoko	0.90	0.96	0.87	0.89	0.83	0.80
Malawi	0.95	0.97	0.90	0.92	0.88	0.82

In the abstract, we propose to replace:

“The GCMs simulate fairly well the unimodal seasonal cycle of precipitation in the Masoko/Malawi region and the bimodal seasonal cycle characterizing the Challa/Naivasha region, except that in the latter the relative magnitude of the two rainy seasons is less well captured.”

by

All GCMs simulate fairly well the unimodal seasonal cycle of precipitation in the Masoko/Malawi region, while the bimodal seasonal cycle characterizing the Challa/Naivasha region is generally less well captured by most models.

In the conclusion, we propose to change:

“When compared to recent observations, the GCM simulations represent the unimodal seasonality of precipitation characterizing the Masoko/Malawi spatial domain fairly well, and also the bimodal seasonality characterizing the Challa/Naivasha domain except that the relative magnitude of the two rainy seasons is less well captured.”

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by

When compared to recent observations (1979-2005), simulations of all GCM models represent the unimodal seasonality of precipitation characterizing the Masoko/Malawi spatial domain rather well. The bimodal seasonality characterizing the Challa/Naivasha domain is generally less well captured by the models, with a systematic underestimation of the long rains and overestimation of the short rains.

Introduction: Southeast and equatorial east African lakes versus east African rainfall. Make as clear as possible at the outset that east African is covering all four lakes but that the distinction between southeast and equatorial east African is how you will describe the two sets of two lakes.

Following the referee's suggestion, we propose to change:

"In this study, we consider proxy records describing the water-balance history of Lake Challa and Lake Naivasha in eastern equatorial Africa, and of Lake Masoko and Lake Malawi in southeastern (but still inter-tropical) Africa (Fig. 1)."

by

In this study, we consider proxy records describing the water-balance history of four East African lakes: Lake Challa and Lake Naivasha in eastern equatorial Africa, and Lake Masoko and Lake Malawi in southeastern (but still inter-tropical) Africa (Fig. 1).

(Page 2, Line 8) "through atmospheric adjustments to the Walker circulation". This statement is unclear to me, perhaps you mean oceanic driven changes to the atmospheric Walker circulation?

It actually depends on the studies. The introduction will be modified in this way:

However, the mechanisms involved are less clear, with Goddard and Graham (1999) and Ummenhofer et al. (2009) suggesting that an ocean-driven change to the atmospheric Walker circulation impacts East African rainfall, while Klein et al. (1999)

mention an atmospheric change affecting both tropical-ocean SSTs and East African rainfall.

(Page 2, Line 23) “Enhanced pattern” perhaps better to say an increase in because you are not talking about a spatial pattern.

This will be modified accordingly.

(Page 2, Line 33) “poor ability” suggest using the inability.

This will be modified accordingly.

(Page 3, Line 1) “reached contrasting conclusions depending on the region or spatial scale, or on the variables and models considered.” Given this, basing any conclusions regarding the role of internal variability on the fact that the models do not match the reconstructions seems problematic given that only two model grid points are being analyzed. A larger spatial scale might provide more confidence here, however the results using the CESM ensemble do provide strong evidence for the role of internal variability.

Actually we use more than 2 grid points, as shown in Fig. 1 of the submitted manuscript and discussed in Section 3.2. Furthermore, we have done the same analysis with modified study areas (including larger ones) and this does not make any substantial change. This will now be specified in Section 3.2:

Lake Challa and Lake Naivasha on the one hand and Lake Masoko and Lake Malawi on the other have a very similar climatology and seasonal cycle in the recent period, both in models and observations (Fig. 2). We thus consider a spatial domain which includes the first two lakes (0.2° N to 4.8° S and 34.2° E to 40.2° E, referred to as the Challa/Naivasha region) and a second one which includes the last two (7.2° S to 12.2° S and 31° E to 37° E, referred to as the Masoko/Malawi region; Fig. 1). Note that shifting or changing the size of these two regions to some extent does not generate substantially different results.

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(Page 3, Line 20) It is not clear how the annual means follow from the long-term changes. Maybe save the discussion regarding the use of annual means portion for later.

Lake level depends, amongst other factors, on rainfall throughout the year. We thus hypothesize that the record is not seasonally biased, which is why we annually average the results of the climate models before smoothing them in order to match the temporal variability of the reconstructions.

(Page 3, Line 22) Is there any reason to suggest that models should capture the reconstructed changes? Perhaps change to analyze GCM simulations of long-term change relative to reconstructions over the last millennium. I do not think this study is truly aimed at investigating GCM performance.

We agree with the referee. This will be modified accordingly.

(Page 4) An aside, but I really appreciate the detail that you have gone into with regards to the set up of the models and the slight differences.

Thanks a lot for this comment.

Section 2.2. I think it is important to note how comparable each of these records are. Are there reasons to expect systematic differences given that they each are reconstructing different things? How might this impact the interpretation of the results and conclusions?

Cf. Our response to the referee's comment on section 4.1: The reconstructions are based on different proxies that have a different relationship with the target climate variable. However, as mentioned in Section 2.2, they are all appropriately sensitive to hydroclimate variation and can thus be qualitatively compared. We propose to add this sentence at the end of Section 2.2 to add clarity:

Although these records are derived from different proxies, their time series can all be qualitatively viewed as smoothed versions of these sites' local moisture-balance

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history, and should thus be related to common signals in their region's hydroclimate history.

Figure 2) On the x-axis Fev should be Feb, the labels overlap so potentially make text smaller.

This will be updated.

(Page 7, Line 15) To my eye CESM1 doesn't look better than the other models, BCC is arguably more realistic, maybe just remove the second part of that sentence.

We agree, the second part of the sentence will be removed.

(Page 8, Line 1) Put a space in "Lake Naivashais"

This will be done.

(Page 8, Line 4) I am not sure the split in how realistic the models are is that clear. When looking at CCSM4, CESM1 and BCC-CSM1-1, IPSL looks just as reasonable to me. Maybe be a bit more general.

This sentence actually refers to the average of all months ("Mean" column in Fig. 2). And although IPSL is not far, only the models CCSM4, CESM1 and BCC-CSM1-1 are in the range of the observations. We propose to rephrase to be clearer about what we are talking about:

For mean monthly precipitation throughout the year at Lake Challa (Fig. 2b), three models are within the range of the observations: CCSM4, CESM1 and BCC-CSM1-1.

(Page 8, Line 13) I think this is a bit of an oversimplification in the second part of this sentence as the timing is also off (not just the magnitude).

We agree and will mention that the timing can also be problematic.

(Page 8, Line 22) "Since Lake Challa and Lake Naivasha on the one hand and Lake Masoko and Lake Malawi on the other have a very similar climatology and seasonal cy-

cle both in models and observations (Fig. 2)”. We are interested in long term changes, nothing that can really be done but the reconstructions for each lake look very different suggesting that on long timescales things might not be expected to be similar.

Yes, this is right. We show in Fig. 2 of the submitted manuscript that Lake Naivasha and Lake Challa on the one hand and Lake Masoko and Lake Malawi on the other hand are strongly linked, based on available recent observations and model results. This is confirmed in Section 3.2 using model results over the last millennium, but this cannot be confirmed using proxy-based reconstructions.

We propose to mention in the sentence cited by the referee that it only refers to the recent period:

Lake Challa and Lake Naivasha on the one hand and Lake Masoko and Lake Malawi on the other have a very similar climatology and seasonal cycle in the recent period, both in models and observations (Fig. 2).

(Page 8, Line 24) “However, using the larger grid boxes raises the issue of whether the proxy-based reconstructions employed to assess model performance through the last millennium are representative for these larger spatial domains”. Be more exact here, don’t use assess model performance. That’s not really what’s being done here.

Following the referee’s comment, we propose to change the sentence by:

However, using larger grid boxes raises the issue of whether the proxy-based reconstructions that are compared to model results through the last millennium are representative for these larger spatial domains.

(Page 9, Line 12) “Regarding annual mean absolute values”. What do you mean by this?

The term “absolute” means that we are talking about the true values, and not about anomalies. This will be specified in the manuscript.

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(Page 10, Line 34) “Nevertheless, with values equal to 0.27 and 0.16 the significant correlation coefficients between, respectively.” Are these spatial correlations? This section is a bit confusing; suggest revisiting with an eye towards clarifying the language.

We agree with the referee. To clarify the section, we propose to change:

“Out of the six GCMs, only CESM1 and MPI-ESM-P correctly simulate the spatial pattern of observed Challa/Naivasha rainfall (Fig. 4a). Nevertheless, with values equal to 0.27 and 0.16 the significant correlation coefficients between, respectively observed and simulated rainfall-SST correlation maps remain relatively low for these two models (Table S2).”

by

Out of the six GCMs, only CESM1 and MPI-ESM-P seem to correctly simulate the spatial pattern of correlations between Challa/Naivasha rainfall and SSTs (Fig. 4a). However, the match with observations is far from perfect as shown by the relatively low correlation coefficients between simulated and observed rainfall-SST correlation maps, with values equal to 0.27 and 0.16, respectively (Table S2).

(Page 12, Line 19) “theright”, put space.

This will be done.

(Page 12, Line 27) “Making abstraction of chronological uncertainties, the Challa and Naivasha proxy records show discrepancy during the first four centuries of the last millennium”. This sentence is confusing.

Cf. above, it will be replaced by:

Notwithstanding chronological uncertainties, the Challa and Naivasha proxy records display clear differences during the first four centuries of the last millennium.

(Page 12, Line 30) “humidity”, suggest changing to wetting.

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We will remove “in humidity”.

(Page 13, Line 7) “Besides”, suggest removing.

This will be done.

(Page 14, Line 2) “thus leads to larger river runoff towards the lakes”. I am not sure that I understand this as the models do not have these actual lakes.

This is right, “towards the lakes” will be removed.

Page 14, Line 5) “This implies that most changes of P-E over time are due to changes in gprecipitation”. Is this necessarily true on longer timescales?

One could indeed expect increasing importance of temperature and thus of evaporation when averaging the results over longer timescales. However, this is not the case in the models (Fig. 2 of this document). Using a loess filter with smoothing window of 100 years, the differences between the standard deviation of precipitation and evaporation drop by a factor of about 10, but the relative amplitudes remain approximately the same to what is shown using annual results, meaning that precipitation still dominates on evaporation.

(Page 15, Line 8) Why not a more typical and interpretable standardization using the standard deviation?

The only reason is aesthetic, dividing by the maximum allows limiting the amplitude of the time series between -1 and 1. In any case, using the standard deviation does not change dramatically the results, as you can see in Fig. 3 of this document.

(Page 15, Line 9) How does this or does this not match the temporal resolution of those reconstructions. I suppose I am just interested in a more thorough justification for this choice of smoothing.

The exact resolution of each reconstruction is variable through time because of the non-linear relationship between sediment depth and age in all four time series. There-

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fore, here we just estimate it at a few decades on average. We chose to smooth the model results using a window of 100 years, which appears to be a good value to make model variability qualitatively similar to that in the reconstruction. Note that we tested several window widths, but this did not change the results significantly. This will be specified in the revised version:

Our choice of 100-year smoothing window is partly subjective, since the resolution of the proxy-based reconstructions varies through time due to a non-linear relationship between sediment depth and age. However, using other window widths for this smoothing does not lead to major changes in the results.

(Page 15, Line 11) [By eye in Figure 7 the model variability looks to be about the same magnitude as the reconstructions.](#)

We consider that the large (multi-)centennial fluctuations visible in the reconstructions are not present in the model results. Indeed, the reconstructions can be positive or negative for several consecutive centuries, while the model curves usually only for a couple of decades (unless one takes into account the memory by using an autoregressive model). Still, we propose to change “much weaker fluctuations” by “weaker fluctuations” to better describe what can be seen on Fig. 7 of the manuscript.

(Page 16, Line 12) [“confronted”, should be compared.](#)

This will be updated.

(Page 17, Line 10) [This is an important sentence. At least remove “that” to make it clear, however, restructuring the sentence would probably be good.](#)

We agree with the reviewer. We propose to modify as follows:

“The fact that all the model results appear different raises the question whether external forcing has any impact on the simulated hydroclimate, forcing that is comparable between models (see Section 2.1) and is thus expected to put a comparable imprint on all time series.”

by

Simulations with different GCMs take into account comparable climate forcing (see Section 2.1), which is thus expected to put a comparable imprint on all time series. However, all model results seem different, which raises the question whether external forcing has any impact on the simulated hydroclimate.

(Page 17, Line 22) “In this regard, it is of interest to note that for the one model for which multiple ensemble members were available (CESM1), there is also no correlation between the different ensemble members that differ only from slightly different air temperature at the start of the experiments (Otto-Bliesner et al., 2015)”. This is very important and gets lost a bit as cast.

We agree with the referee that this is an important sentence. In order to better highlight it, we propose to put a paragraph break just before.

(Section 5.2) I feel like this section would be clearer with the unfiltered pre-industrial control run teleconnections also shown. It becomes a bit confusing with the pre-industrial portion of the last millennium, pre-industrial control runs, and historical simulations all being compared simultaneously.

We think that adding even more material could actually bring confusion in this Section that is indeed already quite dense. Moreover, it contains only one reference to the figure showing the unfiltered pre-industrial control run teleconnections (p.20 l.9), so we prefer to keep this figure in the supplementary material (Fig. S3) .

The historical simulations are not shown in Section 5.2, as is mentioned in its first paragraph. The 3 figures included show the annual teleconnections according to the ‘past1000’ simulations (period 850-1850; Fig.10), and the smoothed teleconnections according to the ‘PI control’ simulations (Fig. 11) and to ‘past1000’ simulations (Fig. 12).

Nevertheless, this section will be modified in the revised version to add clarity.

Conclusion) This ends on a weak note, I might suggest finishing the paper with the last sentence of the previous paragraph.

Actually, we think that this does not end on a weak note, but on a caution that can be important for future studies dealing with hydroclimate as simulated by GCMs. Furthermore, the last sentence of the previous paragraph only relates to the teleconnections, while the last paragraph is more general. We would thus prefer to keep it the way it is.

Interactive comment on Clim. Past Discuss., doi:10.5194/cp-2015-194, 2016.

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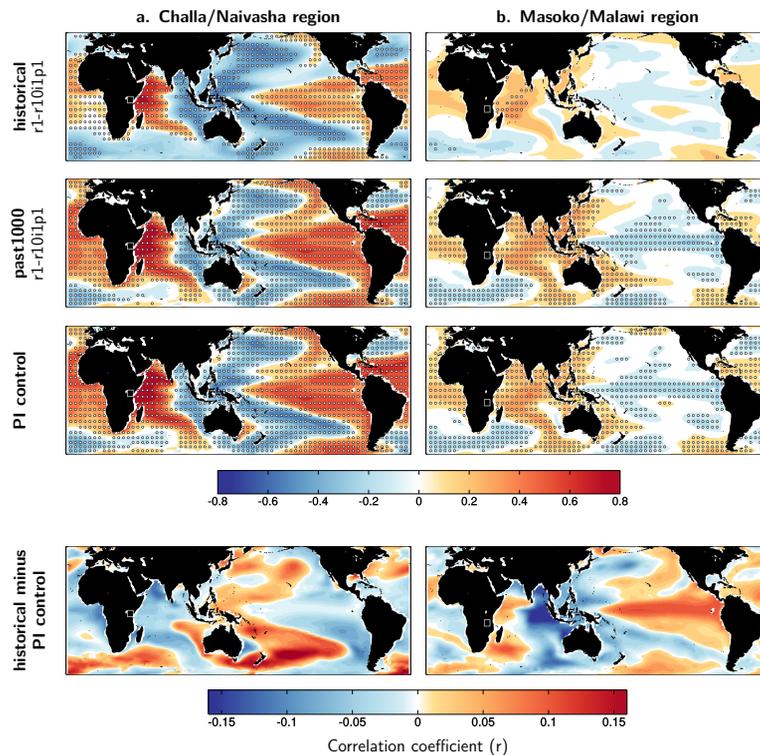


Figure 1 – Pearson correlation coefficients between global SSTs and mean annual rainfall over the Challa/Naivasha region (left) and the Masoko/Malawi region (right), in the 'past1000', 'historical' and 'pre-industrial (PI) control' experiments of CESM1. For 'past1000' and 'historical' simulations (upper 2 rows), the teleconnection pattern shown is the mean of the 10 ensemble members available. In areas overprinted by white circles the null hypothesis of no correlation can be rejected at the 5% level.

Fig. 1.

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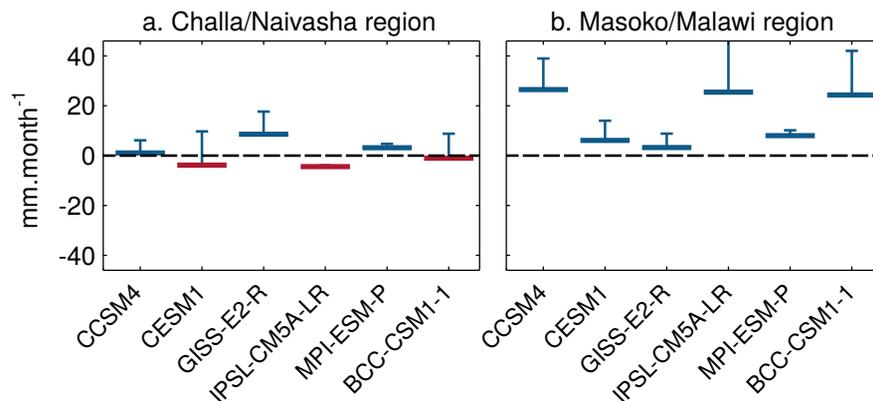


Figure 2 – Mean annual precipitation minus mean annual evaporation (horizontal bars), and standard deviation of annual precipitation minus the standard deviation of annual evaporation (vertical bars) using smoothed results with a window of 100 years. The period considered is the entire last-millennium (850-2005). The differences between the standard deviation of precipitation and evaporation (vertical bars) are multiplied by 10.

Fig. 2.

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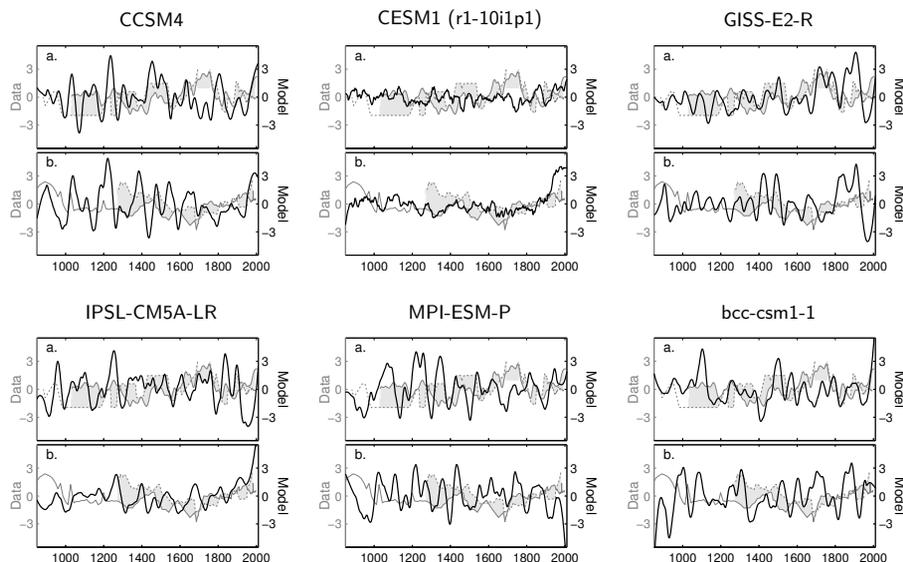


Figure 3 – Comparison between last-millennium time series of the reconstructions (in grey) and of P-E simulated by six GCMs (in black) averaged over the Challa/Naivasha region (a), with the Naivasha record shown as dashed line and the Challa record as solid line; and over the Masoko/Malawi region (b), with the Malawi record shown as dashed line and the Masoko record as solid line. In both regions, the area between the two records is shaded in light grey. Both proxy-based and simulated time series are presented as anomalies with respect to the whole period, and are standardized by being divided by their standard deviation. Ordinate axes are oriented such that wetter (drier) conditions point upwards (downwards). Model time series are annual mean values filtered using a loess method with a window of 100 years. For the CESM1 model, the black curve is the median of the ten ensemble members previously standardized and smoothed.

Fig. 3.

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Interactive comment on “Comparison of simulated and reconstructed variations in East African hydroclimate over the last millennium” by F. Klein et al.

F. Klein et al.

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Received and published: 10 May 2016

- [In blue: referees' comments](#)
- In black: our answers
- *In black italic: what we propose to add in the text*

This paper deals with a very important subject: Comparison of the simulated and reconstructed climate. Working out similarities and differences is key for a better understanding of the climate drivers and their quantification.

The authors have chosen four fairly high-resolution climate curves from East Africa

which they compare with model results. Interestingly, some of the reconstructed climate curves differ markedly. In Figure 5 the Naivasha and Masoko lakes show a dry Medieval Warm Period (MWP) / Medieval Climate Anomaly. In contrast, Challa appears to be more humid, even though the record starts slightly later and the beginning is unclear. In the Lake Malawi climate curve the time 1000-1300 AD is absent, therefore it is unclear if the MWP was dry or wet here. I suggest you add information from Johnson et al. 2004.

According to those authors: “Diatom productivity was high during the Little Ice Age (LIA) and relatively low around 1 kyr, the time of the Medieval Warm Period (MWP)”. The low diatom productivity during the MWP may be linked to low river discharge, i.e. drought conditions. During this time the rivers may have supplied lower amounts of dissolved silica to the lake. During the wetter Dark Ages Cold Period and Little Ice Age, chemical weathering of bedrock intensified and increased the BSi concentrations and diatom productivity in the lake. <http://link.springer.com/chapter/10.1007>

Thank you for your comment. The reconstruction of Johnson et al. (2004) is certainly interesting, but we prefer not to discuss it in the revised version, since it would add complexity to our manuscript (which is already long as underlined by the reviewers) without adding much extra value for the model-data comparison. Indeed, our goal here is not to extensively review the available proxy-based reconstructions of hydroclimate, but to compare model simulations with available reconstructions that have a sufficient temporal resolution to make the comparison meaningful. Nevertheless, we have now mentioned in the Section 2.2 of the manuscript (Proxy-based hydroclimate reconstructions) that comparing to additional records would be an interesting follow up to the present work (see sentence below).

I would like to draw your attention to an ongoing project in which I am mapping the climate characteristics of the MWP on a global scale, based on the large number of published case studies. The interactive online map is freely accessible here: <http://t1p.de/mwp>

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In East Africa you see a large number of yellow points that represent studies which reported drought/arid conditions for the MWP time. When you click on the respective dot, key information from the paper appears, including a link to the key climate curve. Arid conditions seem to be the general pattern that existed 1000-1300 AD in East Africa. The arid MWP belt appears to continue northwards along the coast of the Arabian Sea, including Ethiopia, Yemen, Oman, Pakistan and coastal northwestern India. There, the MWP climate regime seems to change. Southern and eastern India and the Bay of Bengal appear to be humid during the MWP. Mapping is still ongoing and many more studies will have to be integrated. It is also clear that in detail things are more complex. Nevertheless, I think it would be important to initially compare the models to these general, high-level patterns.

Thank you very much for the information. The map is really interesting, showing large-scale features whilst taking into account local patterns. In our manuscript, we have chosen to use the compilation of hydroclimate proxy-based reconstructions for our study region, as done in Tierney et al. (2013). Although your map contains some East African hydroclimate reconstructions that may be interesting to compare with model results, it appears that the number and type of the reconstructions used in our study is not critical to reach our conclusions, given that we suggest that simulated hydroclimate is mainly driven by internal variability in this region. Hence, we do not expect to find much agreement between model results and hydroclimate reconstructions over the last millennium, and, if any was found, it would be coincidental only. However, a comparison with additional records would certainly be interesting to assess the robustness of the changes inferred from the records selected here and to refine the spatial structure of those changes. This is now specified as a possible future perspective of our work, in Section 2.2 of the manuscript (Proxy-based hydroclimate reconstructions):

Several other proxy records exist describing East African hydroclimate variability during the last millennium (Verschuren, 2004; see also <http://t1p.de/mwp>). The majority of these mostly lake-based records do not possess sufficient age control to assess the

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regional coherence of inferred (multi-) decadal and century-scale hydroclimate variation. Since our goal here is not to extensively review the strengths and weaknesses of those individual reconstructions, we follow Tierney et al. (2013) to consider only the handful of records which combine high temporal resolution with adequate age control. However, a critical review of all available records could potentially refine the spatial structure of documented hydroclimate changes and allow further assessment of the robustness of broad-ranging climate-dynamic inferences.

From your study and reference list I have gathered quite a few new publications that I will add to the MWP map in due course. Thanks for that.

Thanks for the comment.

Concerning the forcing of pre-industrial climate change, I am not comfortable with models that gain their simulated climate variability mostly from internal variability. There are clear MWP patterns and additional millennium cycles (e.g. Bond et al. 2001) which point towards powerful external climate drivers. Numerous papers have highlighted the important role that solar activity changes play in the climate equation. I want to encourage you to also run models and scenarios with a solar radiative forcing higher than that assumed by the IPCC. If not for this paper, maybe in a future one. The current RF proposed by the IPCC does not honour the great number of studies which highlight the intense coupling of climate with solar activity changes: <http://chrono.qub.ac.uk/blaauw/cds.html>

Indeed, many studies have emphasized solar forcing of climate change, based on comparison between proxy reconstructions of different climate variables (temperature, rainfall, etc.) and reconstructed solar activity variations. However, the changes in total solar irradiance are small. To induce a significant impact on the climate system, feedback mechanisms are required to amplify these initial changes, but these mechanisms are not well known. Furthermore, previous studies have had trouble to formally detect the influence of solar irradiance on climate of the past millennium and to determine whether

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simulations with low or moderate solar forcing are more realistic (e.g., Schurer et al., 2014; Jungclaus et al. 2010, PAGES2k-PMIP 2015). By contrast, simulations driven by very large solar forcing are not compatible with many available reconstructions. Running new model experiments with enhanced solar forcing could provide insights into this controversial topic, but unfortunately, it will not be possible to include this in the present study.

Here, we have not run any simulations ourselves. Making new simulations covering the last millennium with these GCMs requires a tremendous amount of computer time, in addition to technical expertise adapted to each model. We have thus used the publicly available experiments that were performed by different modeling groups. All those simulations have been performed following the well-defined frameworks (changes in forcing, periods covered by the simulations, etc) of the projects PMIP3 (for the past 1000 simulations, from 850 AD to 1850 AD, Otto-Bliesner et al., 2009) and CMIP5 (for the historical simulations, from 1850 AD to present, Taylor et al., 2012). Making new coordinated model experiments with enhanced solar forcing would thus require a joined and long-term effort, and although potentially very interesting, is out of scope of this study.

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Comparison of simulated and reconstructed variations in East African hydroclimate over the last millennium

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Abstract. The multi-decadal to centennial hydroclimate changes in East Africa over the last millennium are studied by comparing the results of forced transient simulations by six General Circulation Models (GCMs) with published hydroclimate reconstructions from four lakes: Challa and Naivasha in equatorial East Africa, and Masoko and Malawi in southeastern inter-tropical Africa. All GCMs simulate fairly well the unimodal seasonal cycle of precipitation in the Masoko/Malawi region, while the bimodal seasonal cycle characterizing the Challa/Naivasha region is generally less well captured by most models. Model results and lake-based hydroclimate reconstructions display very different temporal patterns over the last millennium. Additionally, there is no common signal among the model time series, at least until 1850. This suggests that simulated hydroclimate fluctuations are mostly driven by internal variability rather than by common external forcing. After 1850, half of the models simulate a relatively clear response to forcing, but this response is different between the models. Overall, the link between precipitation and tropical sea surface temperatures (SSTs) over the pre-industrial portion of the last millennium is stronger and more robust for the Challa/Naivasha region than for the Masoko/Malawi region. At the inter-annual time scale, last-millennium Challa/Naivasha precipitation is positively (negatively) correlated with western (eastern) Indian Ocean SST, while the influence of the Pacific Ocean appears weak and unclear. Although most often not significant, the same pattern of correlations between East African rainfall and the Indian Ocean SST is still visible when using the last-millennium time series smoothed to highlight centennial variability, but only in fixed-forcing simulations. This means that, at the centennial time scale, the effect of (natural) climate forcing can mask the imprint of internal climate variability in large-scale tele-connections.

1 Introduction

In 2011, the Horn of Africa was affected by the most serious drought in decades, leading to severe humanitarian consequences including food and water shortages, acute malnutrition, mass displacement and conflicts (OCHA, 2011; Hillbruner and Moloney, 2012). This drought was followed the next two years by strong pluvial events that triggered floods in Kenya and some parts of Somalia (OCHA, 2012; IFRC, 2013a, b). These consecutive and opposite extreme events illustrate the strong inter-annual variability characterizing East African rainfall (e.g. Nicholson et al., 2012). Due to the seasonal migration of the Intertropical Convergence Zone (ITCZ) back and forth across the equator, rainfall over a major portion of East Africa has a

bimodal annual cycle with a main rainy season during March-May (often referred as long rains) and a weaker rainy season during October-December (often referred as short rains) (e.g. Yang et al., 2015). The short rains are more variable from one year to another, and thus drive most of the observed inter-annual variability (e.g. Hastenrath et al., 1993; Nicholson, 1996, 2014). Numerous studies have emphasised the tele-connection between the East African short rains and either the El Niño/Southern Oscillation (ENSO, e.g. Ogallo et al., 1988; Hastenrath et al., 1993; Nicholson and Selato, 2000; Schreck and Semazzi, 2004; Hoell et al., 2014) or the Indian Ocean Dipole (IOD, e.g. Goddard and Graham, 1999; Saji et al., 1999; Webster et al., 1999; Clark et al., 2003; Ummenhofer et al., 2009; Izumo et al., 2014). However, the mechanisms involved are less clear. Goddard and Graham (1999) and Ummenhofer et al. (2009) suggested that an ocean driven change to the atmospheric Walker circulation impacts East African rainfall, while Klein et al. (1999) mentioned an atmosphere driven change affecting both SSTs and rainfall. In any case, the 2011 drought was triggered by a strong La Niña event (IRI, 2010; Hoell et al., 2014) associated with a negative IOD (JAMSTEC, 2015) that resulted in drier than normal conditions in East Africa during the short rains at the end of 2010. The drought then worsened due to subsequent failure of the long rains in 2011 (Lyon and DeWitt, 2012).

Unlike short rains, the tele-connection between inter-annual East African long rains and the Indian and Pacific oceans is generally considered to be weak (e.g. Mutai and Ward, 2000; Pohl and Camberlin, 2006; Nicholson, 2014). However, failure of the long rains in 2011 was part of a progressive decline in long rains that has started around 1999 (Lyon and DeWitt, 2012) or even earlier (Funk et al., 2008), was associated with abrupt warming of the Indian Ocean (Funk et al., 2008; Williams and Funk, 2011) or of the western tropical Pacific (Merrifield, 2011; Lyon and DeWitt, 2012), also altering the Walker circulation. Merrifield (2011) and Lyon and DeWitt (2012) do not propose a specific cause for this warming. By contrast, Funk et al. (2008) and Williams and Funk (2011) attribute the large-scale shift in Indian Ocean SSTs to anthropogenic forcing, and suggest that a warmer future climate will bring an increased frequency of drought conditions in tropical eastern Africa owing to further reductions in the long rains.

This hypothesis is at odds with general circulation models (GCMs) showing that a warmer climate is associated with an increase in precipitation minus evaporation (P-E) in the intertropical convergence zone (ITCZ), including the East African long rains (Seager et al., 2010; Lañé et al., 2014). Other model-based studies (McHugh, 2005; Shongwe et al., 2011; Kirtman et al., 2013) furthermore suggest that increasingly wetter rainy seasons in East Africa are due to a weakening of the Walker circulation, likely linked to anthropogenic warming (Vecchi et al., 2006; Vecchi and Soden, 2007). This is corroborated by some observations which appear to show a weakening of the Walker circulation already since the mid-19th century (Vecchi et al., 2006). However, there is no agreement on that in observation-based studies, as illustrated by L'Heureux et al. (2013) who found a multi-decadal strengthening of the Walker circulation over the same period. In addition, some regional climate models forced at the boundaries by ensemble-mean GCM results are not consistent with GCMs in that they show a reduction rather than increase in the long rains (Vizy and Cook, 2012; Cook and Vizy, 2013).

The inability of the GCMs in simulating the observed recent downward trend of the long rains implies either that it is part of (multi-)decadal natural variability (Lyon and DeWitt, 2012; Yang et al., 2014; Lyon, 2014), or that the GCMs inadequately represent the climate processes occurring in the region and the response to anthropogenic forcing. In this context, it is crucial to assess the performance of GCMs in simulating East African rainfall. Existing studies on this subject (e.g. Conway et al.,

2007; Anyah and Qiu, 2012; Otieno and Anyah, 2012; Yang et al., 2014) have reached contrasting conclusions depending on the region or spatial scale, or on the variables and models considered. Specifically, they showed that the mean seasonal cycle of precipitation is reasonably well simulated by the majority of GCMs, but that there is a large spread among them in capturing the actual dominant peaks where rainfall is bimodal (Anyah and Qiu, 2012; Otieno and Anyah, 2012). Additionally, most models
5 appear to have significant biases in monthly mean precipitation, and the observed link between East African rainfall and Indian Ocean SST is often not well represented (Conway et al., 2007; Yang et al., 2014).

All the above studies are limited to the recent past where direct measurements of precipitation exist. However, the period considered, which ranges from the last few decades to 150 years at most, is not sufficient to capture the multi-decadal variability that is thought to be an important component of East African hydroclimate (Verschuren, 2004; Tierney et al., 2013). Therefore,
10 to complement those studies, our goal is to extend this analysis to the last millennium by analyzing proxy records of past hydroclimatic change over this period in conjunction with simulations performed in the framework of the third phase of the Paleoclimate Modelling Intercomparison Project (PMIP3; Otto-Bliesner et al., 2009) and of the fifth phase of Coupled Model Intercomparison Project (CMIP5; Taylor et al., 2012). All hydroclimate proxy records available from eastern Africa that are both well-dated and span the last millennium with sufficient time resolution are based on lake-sediment records (Verschuren,
15 2004). [In this study, we consider proxy records describing the water-balance history of four East African lakes: Lake Challa and Lake Naivasha in eastern equatorial Africa, and Lake Masoko and Lake Malawi in southeastern \(but still inter-tropical\) Africa \(Fig. 1\).](#) These four lake records are part of the East African hydroclimate synthesis recently achieved by Tierney et al. (2013), and all characterized by strong multi-decadal to centennial variability. As a consequence, the present study focuses on relatively long-term hydroclimate changes, and on variation in annual means rather than individual rainy seasons, in contrast
20 with model and observation-based studies about variation in recent East African rainfall (e.g. Anyah and Qiu, 2012; Yang et al., 2014).

Specifically, our study [analyzes GCM simulations of long-term hydroclimate change relative to reconstructions over the last millennium](#) to define whether the simulated changes reflect the forcing of external climate drivers and to assess the stability of large-scale tele-connections between East African rainfall and global SSTs. This paper is structured as follows. In Section 2
25 we introduce the model experiments and proxy-based reconstructions. In Section 3 we evaluate the comparative performance of six different GCMs to simulate the seasonal cycle of rainfall over the study regions and its tele-connection to tropical SSTs over the recent period. In Section 4 we analyze the results of model simulations spanning the last millennium. The contribution of forced and internal variability on those simulated hydroclimate changes and the stability of large-scale tele-connections are finally investigated in Section 5, followed by a discussion and conclusions in Section 6.

30 **2 Data and methods**

2.1 PMIP3/CMIP5 model experiments

Climate model simulations from PMIP3 (Otto-Bliesner et al., 2009) and CMIP5 experiments (Taylor et al., 2012) were obtained from the Program for Climate Model Diagnosis and Inter-comparison (PCMDI; <http://pcmdi9.llnl.gov>) and the Earth System

Grid (www.earthsystemgrid.org) archives. The six GCMs selected (Table 1) are those for which the diagnostic variables of interest, i.e. precipitation, actual evaporation and SST, were available at the time of our analysis, for both *past1000* (850–1850 AD) and *historical* (1850–2005) periods, as well as for *pre-industrial control* runs.

Table 1. Modeling centers, parameters and references of the PMIP3/CMIP5 models used in this study.

Model name	Institution	Resolution (lat*lon)		Ensemble members		Reference
		Ocean	Atm.	past1000	historical	
CCSM4	National Center for Atmospheric Research	384*320	192*288	1	6	Gent et al. (2011)
CESM1	National Center for Atmospheric Research	384*320	96*144	10	10	Otto-Bliesner et al. (2015)
GISS-E2-R	NASA Goddard Institute for Space Studies	90*144	90*144	1	6	Schmidt et al. (2014)
IPSL-CM5A-LR	Institut Pierre-Simon Laplace	149*182	96*96	1	5	Dufresne et al. (2013)
MPI-ESM-P	Max Planck Institute for Meteorology	220*256	96*192	1	2	Stevens et al. (2013)
BCC-CSM1-1	Beijing Climate Center, China Meteorological Administration	232*360	64*128	1	3	Wu et al. (2014)

Although not continuous, except for CESM1 and MPI-ESM-P, the first ensemble members (r1i1p1) of *past1000* runs were merged with the corresponding *historical* simulations to obtain results spanning the period 850–2005 AD. The impact of the discontinuity is probably limited since it falls within the range of internal climate variability for surface variables in all cases. The simulations are driven through the last millennium by both natural (orbital, solar, volcanic) and anthropogenic (well-mixed greenhouse gases, ozone, tropospheric aerosols, land use) climate forcings. Earth’s orbital parameters vary according to the calculations of Berger (1978). Depending on the model, different reconstructions of solar irradiance variability are applied. All models except CESM1 and GISS-E2-R use the reconstruction by Vieira and Solanki (2009) from 850 to 1609 and by Wang et al. (2005) from 1610 to 2005. CESM1 uses the reconstruction by Vieira et al. (2011) with the spectral variations and ‘11-year’ solar cycle from Schmidt et al. (2012), whereas GISS-E2-R uses the Steinhilber et al. (2009) reconstruction until 1849 and the Wang et al. (2005) one from 1850 onwards.

The forcing related to volcanic aerosols is derived from Crowley and Unterman (2013) in GISS-E2-R and MPI-ESM-P and from Gao et al. (2008) in the four other GCMs. Reconstructed and observed changes in the major greenhouse gases driving *past1000* (Flückiger et al., 2002; MacFarling Meure et al., 2006) and *historical* (Hansen and Sato, 2004) simulations, i.e. CO₂, CH₄ and N₂O, are the same in all models. Anthropogenic changes in land use/land cover over the last millennium are based on the reconstruction of Pongratz et al. (2008) in MPI-ESM-P, of Pongratz et al. (2008) followed by the reconstruction of Klein Goldewijk and van Dreht (2006) for the historical period in GISS-E2-R and of Pongratz et al. (2009) followed by the reconstruction of Hurtt et al. (2011) for historical time in CCSM4 and CESM1. BCC-CSM1-1 and IPSL-CM5A-LR do not

consider any change in land use/land cover, whose distribution is fixed to the pre-industrial value. Tropospheric ozone and aerosols variations are also taken into account in *historical* experiments in CCSM4, CESM1, GISS-E2-R, MPI-ESM-P and BCC-CSM1-1, and are all based on the dataset described in Lamarque et al. (2010). These changes are however neglected in
5 IPSL-CM5A-LR, which considers a constant concentration fixed at the pre-industrial level. More information on the climate-forcing reconstructions used to drive *past1000* experiments and on their implementation can be found in Schmidt et al. (2011) and Schmidt et al. (2012).

2.2 Proxy-based hydroclimate reconstructions

Despite the relatively large number of lakes present across East Africa, only a small sub-set of them combine continuous
10 sedimentation (and thus, archiving) with hydrological sensitivity to climatic moisture-balance changes (Verschuren, 2003). Recently, Tierney et al. (2013) selected seven East African proxy records that are well-dated and meet the criteria of primarily reflecting hydroclimate variation and of covering the last millennium with a time resolution better than 50 years. Our present study focuses on four of these records, originating from Lake Challa, Lake Naivasha, Lake Masoko and Lake Malawi. The records from Lake Tanganyika and Lake Edward are not considered because they are located far from the Indian Ocean and
15 thus to the west of our region of interest. The record from Lake Victoria is not considered because the representation of this large lake varies from one model to another, which precludes a meaningful comparison between model results and proxy records for this site. Indeed, while most GCMs ignore its presence, the MPI-ESM-P model specifically recognizes it as a surface-water body surrounded by continent. It is well known that Lake Victoria itself strongly influences the regional hydrological cycle (e.g. Thiery et al., 2015), but those effects cannot be adequately reproduced in GCMs with relatively coarse spatial
20 resolution. Several other proxy records exist which describe East African hydroclimate variability during the last millennium (Verschuren, 2004, see also <http://t1p.de/mwp>). The majority of these mostly lake-based records do not possess sufficient age control to assess the regional coherence of (multi-) decadal and century-scale hydroclimate variations. Since our goal here is not to extensively review the strengths and weaknesses of those individual reconstructions, we follow Tierney et al. (2013) to consider only the handful of records that do meet minimum criteria of continuity and hydroclimate signal strength. However, a
25 critical review of all available records might nevertheless refine the spatial structure of documented hydroclimate changes, and allow further assessment of the robustness of broad-ranging climate-dynamic inferences.

The 1000-year time series representing hydroclimate variation in the Lake Challa region developed by Tierney et al. (2013) is the first principal component of the composite variation in three moisture-balance proxies, namely the branched and isoprenoidal tetraether index BIT (a presumed indicator of total annual rainfall: Verschuren et al., 2009; Buckles et al., 2016); δD
30 in the leaf waxes of terrestrial plants (an isotopic proxy for rainfall source and intensity: Tierney et al., 2011); and varve thickness (a proxy for variation in dry-season length and windiness: Wolff et al., 2011). This first principal component accounts for 40% of the variance in the data (supplementary material of Tierney et al., 2013). The time series from Lake Naivasha is a lake-level reconstruction based on sediment lithostratigraphy (Verschuren, 2001), supported by salinity reconstructions based on fossil diatom and midge assemblages (Verschuren et al., 2000). The hydroclimate record from Lake Masoko is inferred from the low-field magnetic susceptibility of the sediment, which is a proxy for lake-level changes and/or wind stress. Two such

records are available for this lake, one that goes back to -43,300 AD (Garcin et al., 2006) and one that starts around 1500 AD (Garcin et al., 2007). The Masoko time series in this paper is obtained from Tierney et al. (2013), who used the last millennium of the longer record but with age-depth tie-points translated from the shorter record (Anchukaitis and Tierney, 2012). Finally, the hydroclimate record from Lake Malawi is deduced from the mass accumulation rate of the terrigenous sediment fraction, presumed to be a runoff proxy (Brown and Johnson, 2005; Johnson and McCave, 2008). Table S1 provides more information about each of these four proxy records. [Although these records are derived from different proxies, their time series can all be qualitatively viewed as smoothed versions of the local moisture-balance history of the corresponding sites.](#)

10 3 Evaluation of model performance over the period 1979-2005

3.1 Mean seasonal cycle of precipitation

This section assesses the ability of various GCMs to reproduce the observed mean state and seasonal cycle of East African rainfall. Although similar analyses have been performed previously (e.g. Conway et al., 2007; Anyah and Qiu, 2012; Otieno and Anyah, 2012; Yang et al., 2014), it is important to repeat it here focusing specifically on the areas where our four study sites are located (Fig. 1).

The number of rain-gauge stations in East Africa is small, and the observations suffer both from an uneven spatial distribution and from gaps in time due to maintenance issues (Dinku et al., 2007; Sylla et al., 2013). We have therefore used global gridded datasets that merge the information from rain-gauge stations, remote sensing, and/or reanalysis results. However, these gridded datasets have their own uncertainties, related for instance to the number and the treatment of rain-gauge measurements or of radar precipitation estimates (Otieno and Anyah, 2013). In order to estimate the effect of these uncertainties on our conclusions, we used four global monthly gridded datasets of precipitation. Version 6 of the Global Precipitation Climatology Centre data set (GPCC-v6; Schneider et al., 2014) is a reanalysis using rain-gauge data only. It spans the period from 1901 to the present with a spatial resolution of $0.5^\circ \times 0.5^\circ$. Version 2.2 of the Global Precipitation Climatology Project (GPCP-v2.2; Huffman et al., 2009) combines rain-gauge and satellite-based precipitation data on a $2.5^\circ \times 2.5^\circ$ grid from 1979 to the present. The Climate Prediction Center (CPC) Merged Analysis of Precipitation data set (CMAP; Xie and Arkin, 1997) covers the same period at identical spatial resolution but combines rain-gauge data and different satellite estimates with NCEP/NCAR reanalysis results in gaps. Finally, NOAA's Precipitation Reconstruction over Land data set (PREC/L Chen et al., 2002) is based only on rain-gauge data and covers the period from 1948 to the present with a spatial resolution of $0.5^\circ \times 0.5^\circ$.

15 Due to the seasonal north-south migration of the ITCZ across the equator, East African rainfall is characterized by a strong annual cycle that differs from one location to another (Nicholson, 1996; Otieno and Anyah, 2013; Yang et al., 2015). The seasonality of rainfall is bimodal over equatorial sites such as Lake Challa and Lake Naivasha, with two rainy seasons occurring in March to May (long rains) and in October-December (short rains), while it is unimodal in the southeastern lakes Masoko and Malawi, with a maximum between November and April during the austral summer (bar charts in Fig. 2). The observed mean monthly rainfall in each of the four study areas over the period 1979-2005 serves as our reference frame to compare the

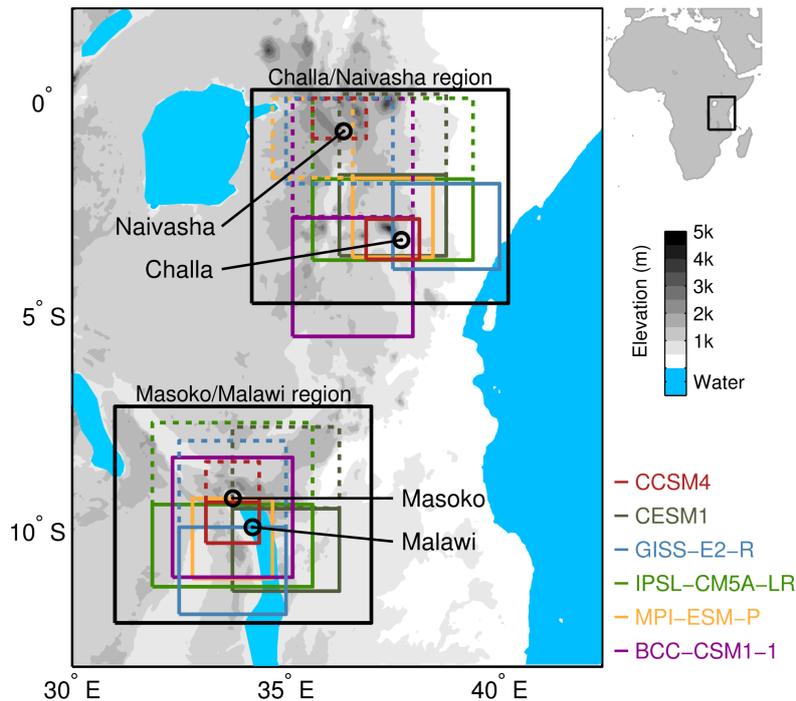


Figure 1. Location of lakes Challa, Naivasha, Masoko and Malawi in East Africa, along with the individual grid cells containing each of these four sites in six different CMIP5 models (dashed (plain) boxes for the grid cells that contain the lakes Naivasha and Masoko (Challa and Malawi)), and the two larger regional domains over equatorial East Africa (Challa/Naivasha region) and southeastern inter-tropical Africa (Masoko/Malawi region). Topography from Amante and Eakins (2009).

5 success of individual GCMs in simulating the present-day seasonal cycle, using model results from the individual grid cells which include the lakes (Fig. 1).

For Lake Naivasha (Fig. 2a), simulated monthly mean precipitation is characterized by a large spread among models. Observed short rains over this lake are relatively well simulated by most models, except by GISS-E2-R and IPSL-CM5A-LR which respectively strongly overestimate and underestimate them. During the other seasons, simulated precipitation over Lake Naivasha is underestimated by all models except GISS-E2-R, including during the main rainy season in boreal spring. Regarding the average of monthly mean precipitation throughout the year at Lake Challa (Fig. 2b), three models are within the range of the observations: CCSM4, CESM1 and BCC-CSM1-1. Most models underestimate the long rains except CESM1 and GISS-E2-R, although in these two models this rainy season is delayed by one month compared to observations. In contrast with the observations, all models show highest rainfall in October or November rather than April, but the spread is again large. These differences between models during the short rains are consistent with biases at larger spatial scales noted in previous studies of the East African region. Anyah and Qiu (2012) and Yang et al. (2014) indeed showed that, despite a large spread among CMIP3 and CMIP5 models, most of them tend to underestimate and to shift by one month the long rains, and to overestimate the short rains. Agreement among models and between models and observations is much higher in Lake Masoko and Malawi

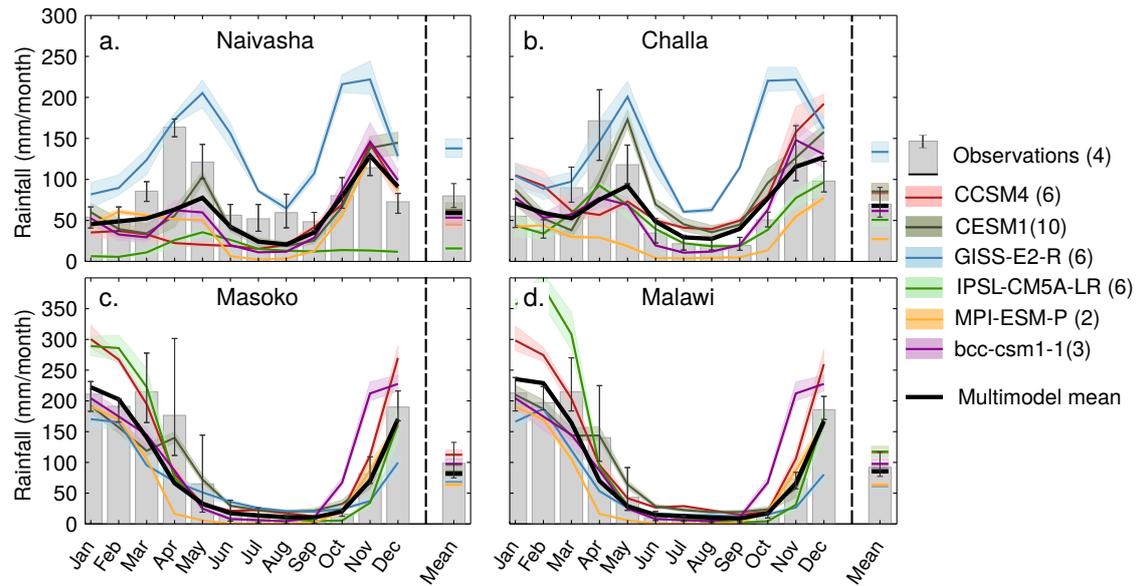


Figure 2. Mean monthly rainfall over lakes Challa, Naivasha, Masoko and Malawi (a-d) in observations (bar plots) and in six CMIP5 models (curves) over the period 1979-2005. The number of datasets (for the observations) or ensemble members (for the models) used in each case is shown in brackets. Error bars and shaded areas represent the range of those observations or ensemble member values.

(Fig. 2c-d). Both the rainy and dry seasons are well simulated, although the amount of rain is overestimated by CCSM4 and
 20 IPSL-CM5A-LR during the rainy season. Overall, climate models used in this study are thus able to represent the unimodal
 rainfall seasonality characterizing the region encompassing lakes Masoko and Malawi, while the **timing and the** magnitude of
 the two rainy seasons characterizing the region encompassing lakes Challa and Naivasha are **in general** less well captured.

Comparing model results and data at individual grid cells can be questionable since model skill at this scale is often very
 limited. For instance, a small shift in the spatial structure of the simulations compared to the observations can lead to large
 25 difference in precipitation. Local topographic features not well represented at the grid scale may also have a significant impact.
 Besides, the surface areas of the grid cells which include the lake sites strongly differ from one model to another (Fig. 1). To
 get rid of the problems linked to differences in spatial resolution and to remove local noise in favour of more regional patterns,
 it seems better to analyze, instead of individual grid cells, larger regions presenting common characteristics as discussed in the
 next section.

30 3.2 Link between individual grid cells and the larger spatial domains selected for analysis

Lake Challa and Lake Naivasha on the one hand and Lake Masoko and Lake Malawi on the other have a very similar climatol-
 ogy and seasonal cycle in the recent period, both in models and observations (Fig. 2). We thus consider a spatial domain which
 includes the first two lakes (0.2° N to 4.8° S and 34.2° E to 40.2° E, referred to as the Challa/Naivasha region) and a second

one which includes the last two (7.2° S to 12.2°S and 31° E to 37°E, referred to as the Masoko/Malawi region; Fig. 1). Note that shifting or changing the size of these two regions to some extent does not produce substantial changes in the results.

However, using larger grid boxes raises the issue of whether the proxy-based reconstructions that are compared to model results over the last millennium are representative of these larger spatial domains. Fig. 3 shows the correlation between modeled mean annual rainfall in the individual grid cells containing the four lake sites and the two larger domains defined for our analysis, for both the recent period and the last millennium. Changes in precipitation within the grid cell containing Lake Masoko, within the grid cell containing Lake Malawi and within the larger box representing the Masoko/Malawi region are highly and significantly correlated for all models and observations, and for both periods. Rainfall over Lake Challa, Lake Naivasha and the Challa/Naivasha region is also positively correlated in both periods for each source of information.

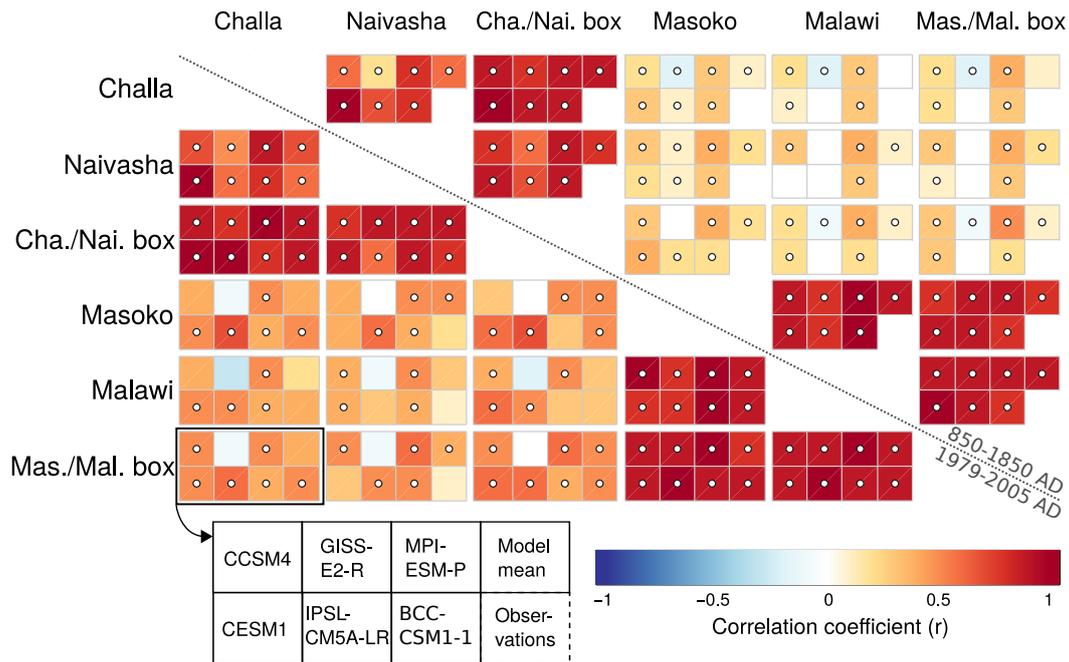


Figure 3. Pearson correlation coefficients between mean annual rainfall values at six different locations: the single GCM grid cells that contain lakes Challa, Naivasha, Masoko and Malawi, and the two larger grid boxes which delineate the Challa/Naivasha and Masoko/Malawi regions. The lower left half of the figure shows these correlations for the period 1979-2005 in the six GCMs considered in this study (CCSM4, CESM1, GISS-E2-R, IPSL-CM5A-LR, MPI-ESM-P, BCC-CSM1-1; only the first ensemble member r1i1p1 is considered) plus the model mean, and in the average of four gridded observation datasets (GPCP-v2.2, CMAP and PREC/L, see references in Section 3.1), in the order shown below the main panel. The upper right half of the figure shows the same results for the period 850-1850 AD (*past 1000*). Squares with a central white circle represent combinations for which the null hypothesis of no correlation can be rejected at the 5% level.

Observed recent rainfall over Lake Challa, Lake Naivasha, and the Challa/Naivasha region shows no or only a weakly positive relationship with rainfall over Lake Masoko, Lake Malawi and the Masoko/Malawi region, underscoring the climatic dichotomy characterizing East Africa. Note that no negative correlation is found except very weak ones in GISS-E2-R between

rainfall over Lake Challa and rainfall over Lake Masoko, Lake Malawi and the Masoko/Malawi region. The dipole between
5 the eastern coastal ‘Horn of Africa’ region and the interior rift-valley region highlighted in Tierney et al. (2013) is thus not
observed at the annual time scale considered here. Although the correlations are quite similar for the recent period and the
last millennium, they are somewhat higher in the former. This may be caused by the present-day anthropogenic forcing that
induces a coherent response between the selected locations within each model.

Overall, both observations and model results show that the two selected regions are on the one hand characterized by different
10 patterns of temporal variability and, on the other hand, representative of the individual grid cells containing the lake sites, not
only regarding annual precipitation changes over the recent period and the last millennium, but also regarding seasonal cycles
and annual mean absolute values (not shown).

3.3 Large-scale tele-connections

In addition to the evaluation of the mean state, it is important to assess the ability of climate models to represent the observed
15 patterns associated with the inter-annual variability of East African rainfall. Although it is not our goal here to study the
mechanisms responsible for the simulated variability, this is illustrated by analyzing the correlations between East African
precipitation and tropical SSTs. The latter is indeed considered as a direct driver of precipitation over East Africa (e.g. Goddard
and Graham, 1999; Ummenhofer et al., 2009). Two different SST datasets are used: version 3 of the Hadley Centre dataset
(HadSST3; Kennedy et al., 2011a, b), based on in-situ measurements covering the period from 1850 to 2015 on a $5^\circ \times 5^\circ$ grid,
20 and version 3b of the Extended Reconstructed Sea Surface Temperature dataset (ERSST-v3b; Smith et al., 2008), also based
only on in-situ data, which covers the period 1854 to 2015 on a $2^\circ \times 2^\circ$ grid. Since the proxy-based reconstructions used in
this study are considered to represent mean annual conditions, interest is here mainly on mean annual results. However, mean
annual results for East Africa’s hydroclimate represent a combined picture, as the relative amplitudes and the strength and
character of tele-connections between East African rainfall and tropical SSTs at the inter-annual time scale are different from
25 one season to another.

For both regions, the largest correlations between observed rainfall and SSTs are found during the boreal autumn (OND),
with the well-known pattern of positive (negative) correlation between East African rainfall and western (eastern) Indian Ocean
SSTs, as well as SSTs in the central/eastern (western) equatorial Pacific (Fig. S1 and S2 OND), which resembles the SST
pattern during an El Niño phase of ENSO and a positive phase of the IOD. This period corresponds to the short rains season in
30 Challa/Naivasha and to the start of the single rainy season in Masoko/Malawi farther south (Fig. 2). For the other seasons, the
spatial pattern of correlations differs between the two study areas, with the greatest difference occurring during boreal winter
(JFM). In Challa/Naivasha, where rainfall is relatively low during this transition period between the short rains and the long
rains, it appears to be positively correlated with SSTs over the central/north Indian Ocean (Fig. S1 JFM). In contrast, just a few
isolated significant correlations are found between rainfall in boreal winter over Masoko/Malawi and tropical SSTs (Fig. S2
35 JFM), although this period marks the annual maximum in precipitation (Fig. 2). Tele-connections to tropical SSTs are weak in
both regions during the boreal spring (AMJ; Fig. S1 and S2 AMJ), which corresponds to the long rains in Challa/Naivasha and

to the end of the rainy season in Masoko/Malawi; and are also weak also during the boreal summer (JAS; Fig. S1 and S2 JAS), which is the principal dry season in both regions (Fig. 2).

When considering mean annual results, the correlations between observed precipitation over the Challa/Naivasha region and SSTs show a pattern similar to that during the short rains, although damped, with positive correlations in the western Indian Ocean and central/eastern tropical Pacific and negative ones centered on Indonesia (Fig. 4a left). In contrast, the correlations between Masoko/Malawi rainfall and SSTs after computing annual averages are mostly weak and non-significant in the Indian Ocean and negative over the Indonesian region while some zones in the Pacific show positive correlations (Fig. 4b left), even though the correlations pattern for boreal autumn (OND) rainfall is similar to that found using precipitation over Challa/Naivasha. In both cases, the spatial pattern of correlations derived from the different combinations of datasets show very similar results, with spatial correlations of the obtained patterns always exceeding 0.80.

Out of the six GCMs, only CESM1 and MPI-ESM-P seem to simulate relatively well the spatial pattern of correlations between Challa/Naivasha rainfall and SSTs (Fig. 4a). However, the match with observations is far from perfect as shown by the relatively low correlation coefficients between simulated and observed rainfall-SST correlation maps, with values equal to 0.27 and 0.16, respectively (Table S2). GISS-E2-R, IPSL-CM5A-LR and BCC-CSM1-1 display totally different patterns compared to observations, and CCSM4 even simulates an opposite pattern, with positive (negative) correlations between simulated precipitation over the Challa/Naivasha area and the eastern Indian Ocean (central/eastern Pacific).

Model results show a wide range of tele-connections between Masoko/Malawi rainfall and SSTs (Fig. 4b.). None of them shows the observed pattern of correlations, which is weak but seems robust given that it is similar regardless of the combinations of datasets used. GISS-E2-R, IPSL-CM5A-LR and MPI-ESM-P correlations patterns are positively, although poorly, correlated with the data (Table S2). However, the correlation coefficients obtained by GISS-E2-R and IPSL-CM5-LR are the result of a compensative effect between wrong seasonal tele-connection patterns (Fig. S2). CCSM4 simulates a strong relationship between Masoko/Malawi and Indian and Pacific Ocean SSTs, but in an opposite sign than expected, with negative correlations in the western Indian Ocean and central/eastern equatorial Pacific, and positive correlations in the eastern Indian Ocean. Although CESM1 can simulate the pattern observed in boreal winter, no correlation is found when considering annual mean results.

Overall, most climate models fail to simulate observed tele-connections of Challa/Naivasha and of Masoko/Malawi rainfall to large-scale SST patterns at the inter-annual scale. Annual smoothing makes these tele-connections complex and of relatively limited magnitude, especially for Masoko/Malawi rainfall. However, this cannot by itself explain the low model performance since their skill is not greatly improved when only considering the OND rainfall, shown to be strongly and robustly correlated to Indian and Pacific SSTs in observations. Only CESM1, MPI-ESM-P and, to a lesser extent, BCC-CSM1-1 simulate the observed patterns for both regions during this season (Table S2). Inconsistent with the observations, IPSL-CM5A-LR and GISS-E2-R simulate a relatively homogeneous tele-connection pattern throughout the year, while the strong seasonality depicted by CCSM4 has almost everywhere incorrect signs. MPI-ESM-P and CESM1 thus tend to stand out by their positive correlation with annual observations in both regions and only in Challa/Naivasha, respectively, for the right reasons. These mitigated results are, to some extent, consistent with the study of Rowell (2013). Indeed, although using different method-



Figure 4. Pearson correlation coefficients between mean annual rainfall over the Challa/Naivasha region (a, upper three rows) or Masoko/Malawi region (b, lower three rows) and global SSTs in observations and climate models (here, only the first member r1i1p1 is used) for the period 1950-2000. In areas overprinted with white circles, a null hypothesis of no correlation can be rejected at the 5% level. No data are available from grey areas.

ologies and selected areas, this author has shown that the tele-connections between rainfall over central East Africa (roughly corresponding to the Masoko/Malawi region) and both equatorial Pacific and Indian Ocean SSTs are particularly hard for

CMIP5 models to reproduce. Furthermore, Rowell (2013) reached a similar conclusion about the tele-connections between rainfall over the greater Horn of Africa region, which includes the Challa/Naivasha region, and equatorial Pacific SSTs.

5 4 Reconstructed and simulated hydroclimate over the last millennium

4.1 Hydroclimate changes deduced from proxy-based reconstructions

Notwithstanding chronological uncertainty, the Challa and Naivasha proxy records display clear differences during the first four centuries of the last millennium. In particular, the former shows a general drying trend while the opposite is recorded in the latter (Fig. 5). However, from around 1400 AD the conditions inferred from these two records are similar: both show relatively dry conditions followed by a wetting trend peaking between about 1700 and 1750 AD. After this peak, both hydroclimate reconstructions depict an abrupt transition towards a dry period in the early 19th century, followed by smaller-scale hydroclimate fluctuations at Naivasha and a clear wetting trend at Challa.

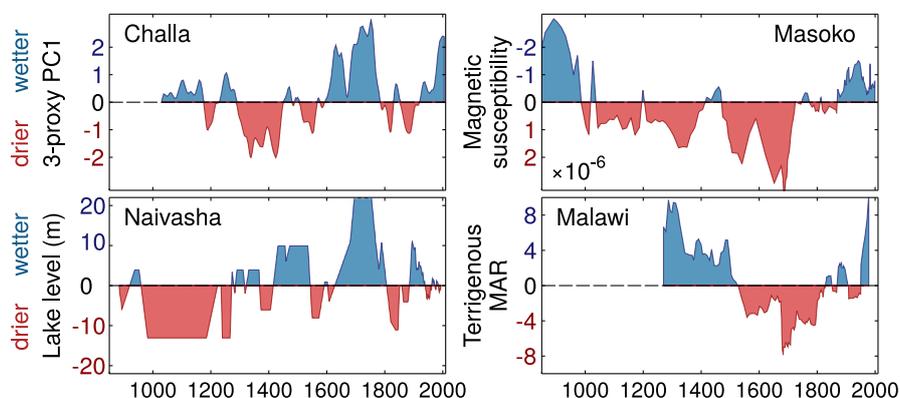


Figure 5. Lake-based moisture-balance reconstructions used in this study; references with details on the proxies are provided in Section 2.2. Ordinate axes for each proxy are oriented such that wetter (drier) hydroclimate conditions point upward (downward).

Contrasting with Challa and Naivasha, lakes Masoko and Malawi both show a general drying trend culminating around 1700 AD, before an increase in humidity towards the present. However, (multi-) decadal hydroclimate changes overlying these long-term trends often strongly differ between the two records.

The differences between the Challa and Naivasha reconstructions on the one hand and between the Masoko and Malawi reconstructions on the other can be viewed as a measure of how representative these records are of hydroclimatic variability within each region. Certainly, the differences partly reflect real local features due to different exposure to the principal seasonal moisture sources related to distance to the sea, topography etc. However, a significant fraction of the difference observed within each pair of records is likely due to uncertainty in the reconstructions themselves, due to the compound effects of i) dating uncertainty in these lake-based proxy records, ii) differences in hydrology and local catchment processes influencing a lake's (or in the case of δD , its surrounding vegetation) sensitivity to climate, and/or iii) the fact that the used hydroclimate proxies

have a specific and different relationship with temporal variation in our target of reconstruction, i.e. the climatic moisture balance. Importantly, the point here is that the differences between the two pairs of records are larger than those within each pair. Each pair can thus be considered as representative of a distinct hydroclimatic region (cf. Tierney et al., 2013).

5 4.2 Interpretation of proxy-based reconstructions from a model perspective

Lakes are complex hydrological systems. To understand their dynamics, it is necessary to account for the inflow and outflow from rivers and surface runoff, rainfall on the lake surface, evaporation from the lake surface, groundwater inflow and/or outflow, as well as interactions with the aquifer surrounding the lake (e.g. Becht and Harper, 2002). These processes are not represented directly in relatively coarse-resolution GCMs. These models simulate the large-scale moisture balance, i.e. precipitation minus actual evaporation (P-E), the latter depending on potential evaporation and soil moisture content. Each of the sedimentary proxies used in the lake-based climate reconstructions can be qualitatively interpreted as smoothed versions of the local-to-regional climatic moisture balance, at least when considered on multi-decadal to centennial time scales. P-E is thus the model variable that has been chosen here for comparison with the reconstructed histories of lake-level fluctuation, catchment runoff or drought-season severity, depending on the lake (see Section 2.2). This section describes the relative contributions of rainfall and of evaporation in P-E, which allows knowing whether the respective regions containing each record are more influenced by precipitation or evaporation.

It was shown in Section 3.1 and in Section 3.2 that, despite their relative proximity, the two spatial domains used in this study, Challa/Naivasha and Masoko/Malawi, are quite different in terms of precipitation amount and seasonality as well as in precipitation trends through time. The study of P-E balance confirms that. Indeed, climate models simulate mean P-E values over Challa/Naivasha which are close to zero throughout the last millennium (Fig. 6a). In contrast, all models show positive P-E values for the Masoko/Malawi region during the last millennium (Fig. 6b). The higher P-E for Masoko/Malawi compared to Challa/Naivasha is as expected due to higher precipitation, which more than compensates for higher evaporation and thus leads to larger river runoff.

If we consider the standard deviation of variation in P and E through the last millennium, there is a consensus among models that P is more variable from year to year than E, for both regions (vertical bars in Fig. 6, which all plot upwards). This implies that most changes of P-E over time are due to changes in precipitation. Differences between the standard deviation of P and of E are also generally greater in Masoko/Malawi. This can be explained in all models except GISS-E2-R by a weaker relationship between P and E in this region than in Challa/Naivasha, as evidenced by weaker correlation coefficients (Table 2). Higher correlations indeed mean that a change in P is more often accompanied by a similar change in E, which tends to bring variances closer.

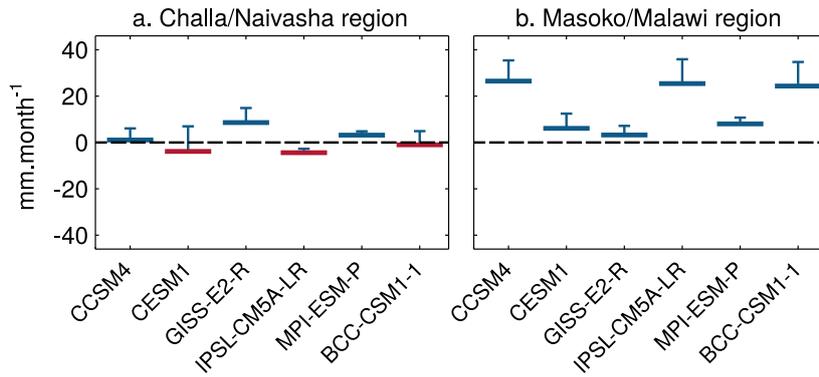


Figure 6. Mean annual precipitation minus mean annual evaporation (horizontal bars), and standard deviation of annual precipitation minus the standard deviation of annual evaporation (vertical bars) using the entire last-millennium results (850–2005) for each GCM. Red (blue) color means that evaporation (precipitation) dominates.

Table 2. Pearson correlation coefficients between simulated rainfall and simulated evaporation in the Challa/Naivasha and Masoko/Malawi regions over the pre-industrial portion of the last millennium (850-1850 AD).

	Challa/Naivasha	Masoko/Malawi
CCSM4	0.66*	0.09*
CESM1	0.57*	0.35*
GISS-E2-R	0.71*	0.95*
IPSL-CM5A-LR	0.91*	0.69*
MPI-ESM-P	0.68*	0.62*
BCC-CSM1-1	0.88*	0.70*

* significant at the 5% level

These results are robust throughout the last millennium where they remain relatively stable over time, even during the 5 recent past where one could expect evaporation to increase relative to precipitation due to anthropogenic warming (not shown). Moreover, rainfall still has a dominant role in explaining changes in P-E when considering timescales longer than annual, since approximately the same picture is observed when filtering model results using a loess method with a window of 100 years (not shown).

4.3 Comparison between reconstructions and model results

10 As briefly discussed in Section 4.2, the link between simulated and reconstructed variables is only indirect, which means that the magnitude of simulated P-E that should best fit the reconstructions is unknown. Consequently, the focus in this comparison is on common relative changes, rather than on their magnitude in absolute values. For better readability of the figures, each time series has been linearly standardized so that the maximum of the absolute values equals 1. A 100-year smoothing is applied to

the model results in order to resemble temporal variability in the reconstructions. Our choice of a 100-year smoothing window is partly subjective, since the resolution of the proxy-based reconstructions varies through time due to a non-linear relationship between sediment depth and age. However, using other window widths for this smoothing does not lead to major changes in the results.

Despite this smoothing, most model curves do not show any distinct long-term trend in the past millennium as observed in the proxy-based reconstructions, and have weaker fluctuations at the centennial scale than the reconstructions (Fig. 7). The correlation coefficients between model results and reconstructions, computed annually using interpolations for the reconstructed time series, are presented in Table S3. Most coefficients are low and non-significant at the 0.05% level, and can be for a same site either positive or negative depending on the models, which implies that there is no common signal between models and data but neither among models.

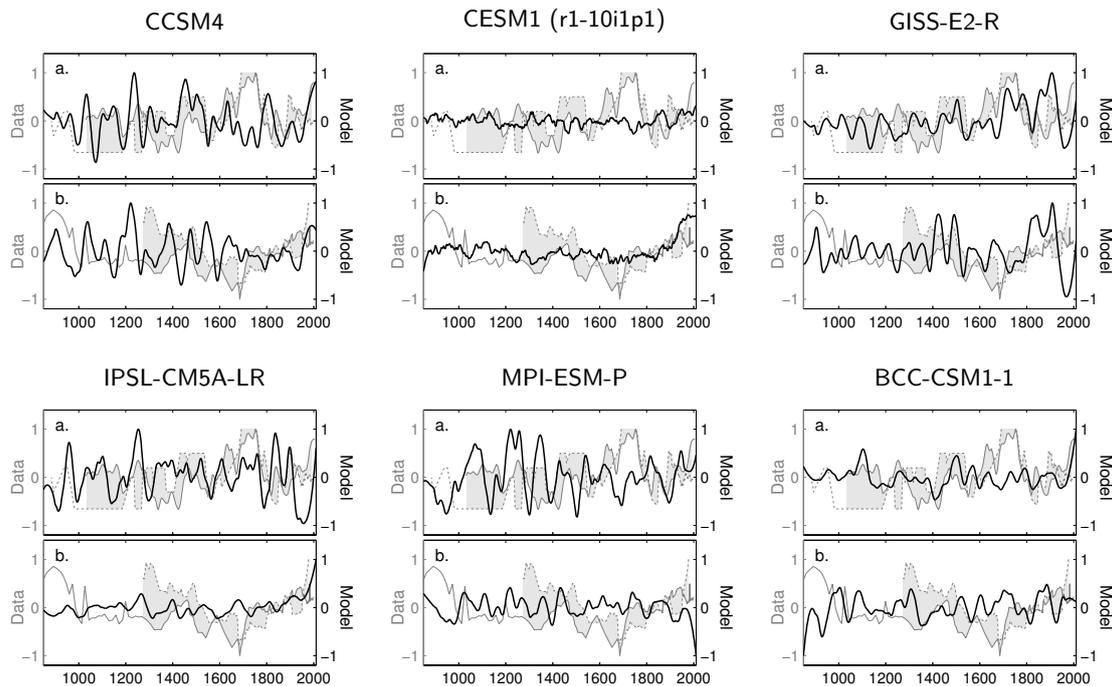


Figure 7. Comparison between last-millennium time series of the reconstructions (in grey) and of P-E simulated by six GCMs (in black) averaged over the Challa/Naivasha region (a), with the Naivasha record shown as dashed line and the Challa record as solid line; and over the Masoko/Malawi region (b), with the Malawi record shown as dashed line and the Masoko record as solid line. In both regions, the area between the between the two records is shaded in light grey. Both proxy-based and simulated time series are presented as anomalies with respect to the whole period, and are linearly standardized so that the absolute maximum equals 1. Ordinate axes are oriented such that wetter (drier) conditions point upwards (downwards). Model time series are annual mean values filtered using a loess method with a window of 100 years. For the CESM1 model, the black curve is the median of the ten ensemble members previously standardized and smoothed.

No individual site is characterized by an overall better agreement between model and data since the averages of correlation coefficients for each lake are close to zero. Furthermore, taking the four sites into account, no model appears to match substantially better the reconstructions than another. Nevertheless, some isolated positive correlations should be mentioned: CESM1 shows one positively and statistically significant correlation of 0.43 with the average of the reconstructions from Masoko and Malawi, and GISS-E2-R correlates with the average Challa/Naivasha time series with a coefficient of 0.38.

This general model-data mismatch could arise from several reasons. First, as discussed in Section 3.2, the results from climate models are selected from the two regions Challa/Naivasha and Masoko/Malawi, that do not necessarily match the spatial representativity of proxy data, or may have trouble in representing the regional atmospheric dynamics responsible for changes in lake hydrology. Note that if we consider only the individual grid cells which contain the proxy data sites, the correlation coefficients are not substantially affected (not shown). This is consistent with the high correlations found for each model simulation between the individual grid cells and the larger spatial domain which contains them (Fig. 3). Second, the variables compared are different. Here, simulated regional P-E is indeed compared to reconstructed lake level, catchment runoff, or seasonal drought severity depending on the site (see Section 2.2). P-E, which mostly depends on variation in precipitation (see Section 4.2), is certainly related to these reconstructed variables, but sometimes in an indirect way that is difficult to assess precisely. Third, our model results only consider the immediate effect of P-E and do not account for long-term effects of a change in P-E. However, lake level during a particular year strongly depends on lake level during previous years. To address this issue, we applied a first-order autoregressive model (AR-1) to each simulated time series. The AR-1 process is a simple persistence model where a realization of the system depends on the value at one time step earlier. This thus allows emulating a system with a chosen amount of memory. However, although this produces time series with low-frequency changes that are similar to the reconstructions, general model-data agreement is not substantially improved (Section A3).

Simulations with different GCMs are driven by similar climate forcings (see Section 2.1), which are thus expected to put a similar imprint on all time series. However, all model results seem different, which raises the question whether external forcing has any impact on the simulated hydroclimate. The lack of common timing among models in the simulated events actually suggests that the hydroclimate fluctuations are mostly or exclusively driven by internal variability.

5 The contribution of forced and internal variability in simulated hydroclimate changes

5.1 Hydroclimate changes over the past millennium

Whether the simulated East African hydroclimate results from internal variability or from changes in forcing is assessed in two steps: first by investigating potentially common signals among models, and second by comparing variability of the last-millennium hydroclimate changes against control simulations. In the previous section we suggested that little or no link can be established between last-millennium hydroclimate changes simulated by the different models. Indeed, if we first consider the Challa/Naivasha region, most correlations between P-E time series simulated by different models are not statistically significant and close to zero (Fig. 8). Actually, the fact that there is no positive correlation between hydroclimate curves from different

models does not necessarily mean that there is no impact of forcing in each model. Indeed, the effect of changes in forcing may be different from one GCM to another, especially at the still relatively small spatial scale considered in this study.

In this regard, it is of interest to note that for the one model for which multiple ensemble members were available (CESM1), there is also no correlation between the different ensemble members that differ only in slightly different air temperature at the start of the experiments (Otto-Bliesner et al., 2015). This means that the forced response has a much smaller magnitude than internal variability for P-E in that region, even at the multi-decadal time scale.

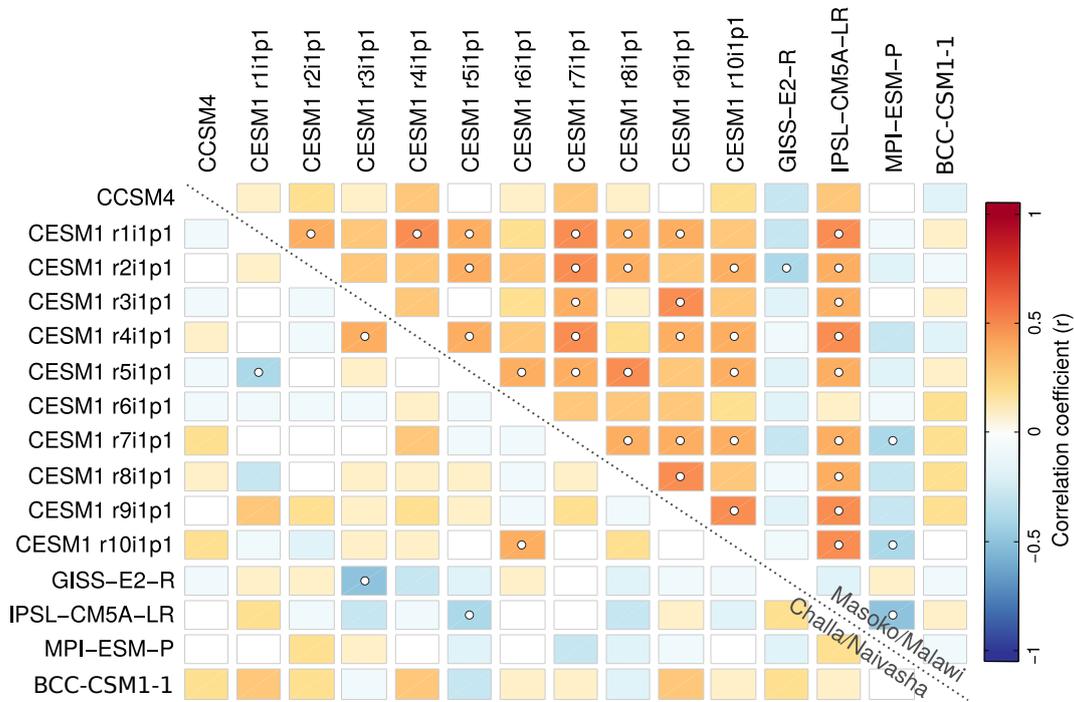


Figure 8. Pearson correlation coefficients between annual mean P-E over the last millennium (850-2005) as simulated by the different GCMs. The results were filtered using a loess method with a window of 100 years. The lower left half of the figure shows the results for the Challa/Naivasha region, the upper right half the results for Masoko/Malawi. Squares with a central white circle represent combinations for which the null hypothesis of no correlation can be rejected at the 5% level.

For the Masoko/Malawi region, the link between the hydroclimate time series produced by different models is also low. However, most ensemble members of CESM1 show significantly positive correlations with each other, mainly due to a common increase in P-E around 1800. This suggests an impact, although limited, of external forcing on Masoko/Malawi hydroclimate during the last two centuries, as simulated by CESM1. For the other models, if a significant response to forcing is present, it is too different between them to be revealed by the correlation, except for IPSL-CM5A-LR which correlates positively with the ensemble members of CESM1.

To complement this diagnostic, Fig. 9 shows P-E time series for the two regions from forced simulations, along with the variability in these time series and in the *pre-industrial control* runs, represented by the ± 2 standard-deviation envelope. It

5 shows that the P-E variance simulated over the last millennium is in most cases very similar to that of the control simulations. This indicates that the radiative changes from GHGs, solar variability and relatively short-lived volcanic effects have little influence on the selected variables compared to internal variability. The only noticeable difference in these variances is found for Masoko/Malawi in two of the models, CEMS1 and IPSL-CM5A-LR, which both show a P-E increase in recent time. The similarity of the variances of P-E in fixed and time-varying forcing experiments, along with the lack of common P-E changes

10 in the last-millennium simulations among models, obviates the possibility of general agreement with the proxy results, and suggests that any apparent proxy-model agreement for this time period and these regions is coincidental. To obtain more information on the processes driving the simulated hydroclimate changes over the last millennium, the next section deals with the stability of tele-connections at different frequencies, and with the impact of changes in forcing on those tele-connections.

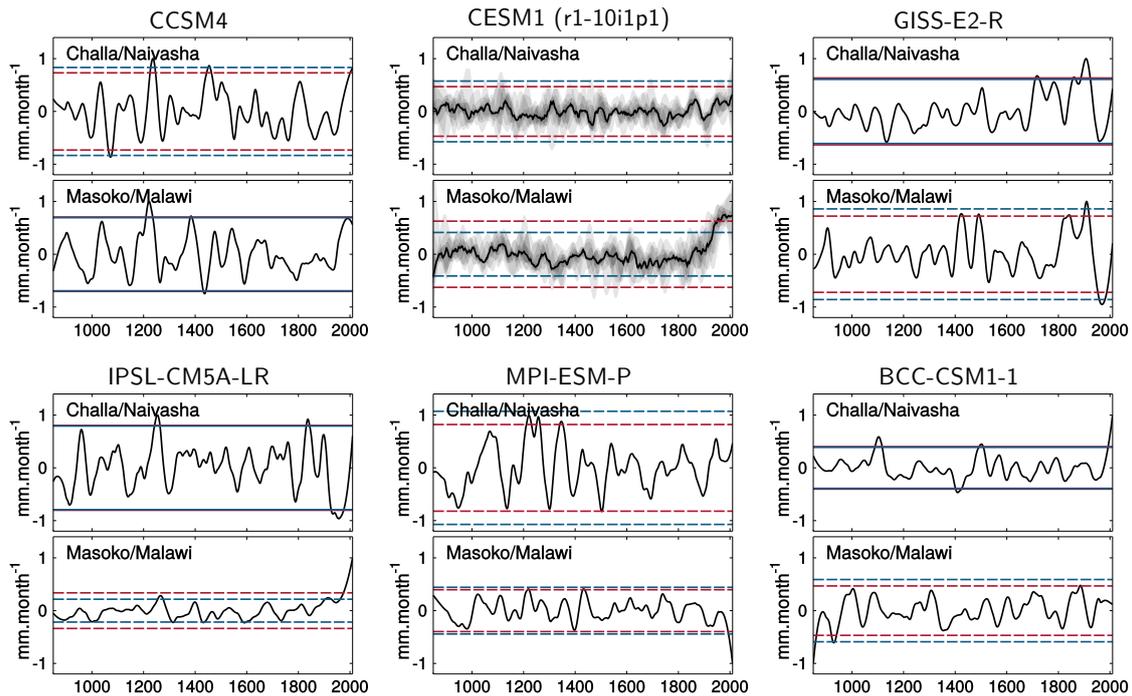


Figure 9. Simulated time series of P-E (black lines) over the Challa/Naivasha and Masoko/Malawi regions throughout the last millennium (850-2005). Results are mean annual values smoothed using a loess filter with a window of 100 years, and are presented as anomalies with respect to the entire period. The horizontal red lines are displayed on both sides of the zero line at two times standard deviation of the smoothed time series. The horizontal blue lines also represent 2 standard deviations on both sides of zero but based on the time series from pre-industrial control simulations. The horizontal lines are dashed if the variance of the simulation with time-varying forcing is significantly different (F-test, considering a 5% level) from the variance of the simulation with fixed forcing; if not, it is solid. For the CESM1 model, the black line is the median of the ten ensemble members, while their range is shown in grey shading.

5.2 The stability of large-scale tele-connections

Since East African hydroclimate fluctuations in models are mostly driven by rainfall (see Section 4.2), only rainfall is considered here. The modern-day large-scale tele-connections have already been studied in Section 3.3. Hence, the period considered in this section is 850-1850 AD, which allows us to focus on the last millennium without the influence of anthropogenic forcing.

Annual mean large-scale tele-connections between simulated East African rainfall and tropical SSTs over the (pre-industrial portion of the) last millennium differ substantially among models. However, for rainfall over the Challa/Naivasha region, all GCMs except CCSM4 agree in simulating a dipole pattern over the Indian Ocean, with positive (negative) correlations in the western (eastern) half of the basin (Fig. 10a), i.e. consistent with the IOD pattern and its effect on East African precipitation. Interestingly, while CCSM4, CESM1 and MPI-ESM-P do not show much difference between last-millennium and recent tele-connections, this dipole is not simulated by GISS-E2-R, IPSL-CM5A-LR and BCC-CSM1-1 with recent rainfall data (1950-2000; Fig. 4a). The role of equatorial Pacific SSTs during the last millennium is less clear among models, with both positive and negative correlations depending on the model selected.

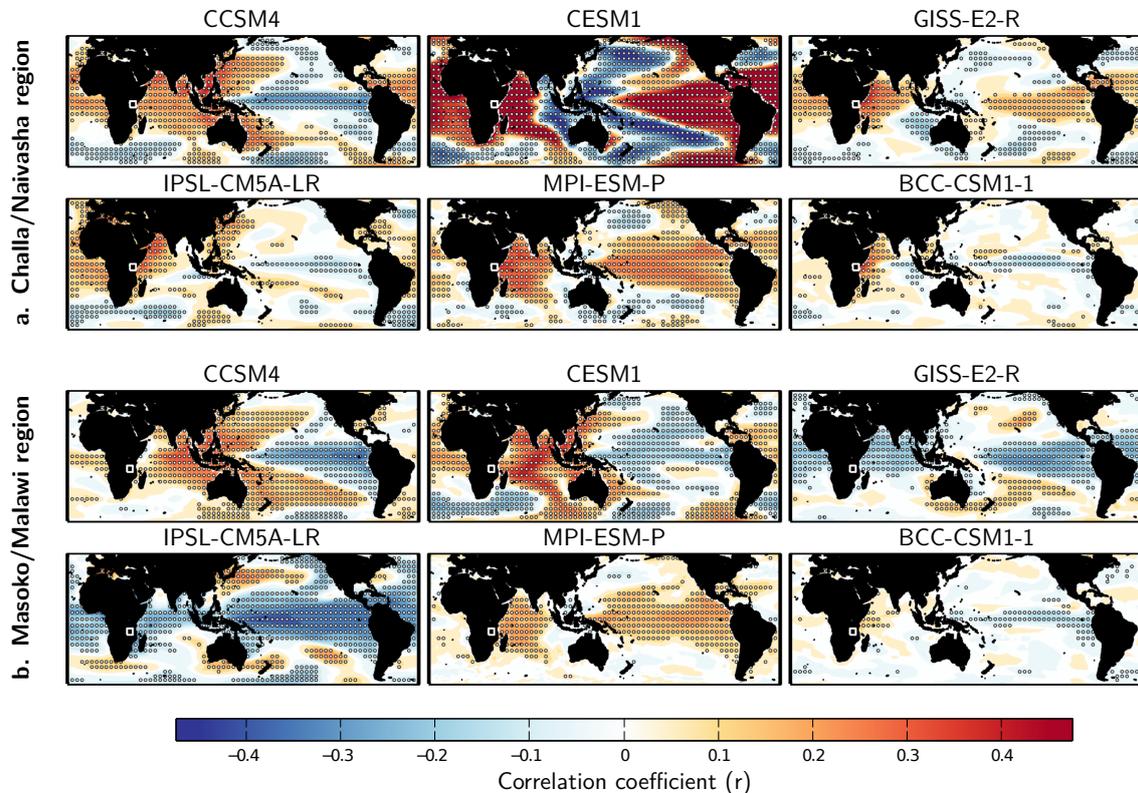


Figure 10. Pearson correlation coefficients between global SSTs and mean annual rainfall over the Challa/Naivasha (a) and Masoko/Malawi (b) regions, in climate models for the period 850-1850 AD. In areas overprinted by white circles the null hypothesis of no correlation can be rejected at the 5% level.

Patterns of correlations between simulated Masoko/Malawi rainfall and SSTs are more heterogeneous (Fig 10b). CCSM4 and MPI-ESM-P show a comparable picture as with Challa/Naivasha rainfall, which is also the case for CESM1 but only for the Indian Ocean. GISS-E2-R and, to a lesser extent, IPSL-CM5A-LR show an opposite pattern, and BCC-CSM1-1 suggests almost no link between Masoko/Malawi rainfall and SSTs. For this region, the pre-industrial last-millennium tele-connections differ strongly from the recent ones in all models except CCSM4 and GISS-E2-R (Fig. 4b). For this pre-industrial last-millennium period, the effect of changes in forcing on inter-annual rainfall tele-connections appears to be weak, given the very similar results of the last millennium runs (Fig. 10) and of the *pre-industrial control* runs for both regions (Fig. S3). It is thus likely that the difference in tele-connection patterns between the pre-industrial period and recent decades, **observed in the models GISS-E2-R, IPSL-CM5A-LR and BCC-CSM1-1**, is due to anthropogenic forcing. Based on the control runs of two global climate models, Tierney et al. (2013) showed that at longer than decadal time scales, rainfall over the Horn of Africa region (including our Challa/Naivasha domain) is mostly influenced by Indian Ocean SSTs. This is investigated here using smoothed GCM-simulation results with a window of 100 years. Such a smoothing decreases drastically the number of degrees of freedom resulting in only a few statistically significant patterns of correlation in control simulations (Fig. 11). As regards simulated Challa/Naivasha rainfall, the correlation with SSTs displays the characteristic Indian Ocean dipole in all models except CCSM4. The dipole is especially clear and robust in CESM1, the model that best matches observations regarding recent large-scale tele-connections (Section 3.3). By contrast, at this centennial time scale, the link between Masoko/Malawi rainfall and the Indian Ocean is neither consistent among models nor robust in these control simulations. Additionally, for neither Challa/Naivasha nor Masoko/Malawi a significant link is obtained with Pacific SSTs.

The patterns of correlations become completely different when considering the **smoothed** last millennium simulations with changes in forcing (Fig. 12). Most correlations are not significant and relatively weak. Interestingly, in the forced runs no Indian Ocean dipole is observed in most model results at this centennial time scale and, more generally, there is substantial difference in modeled large-scale tele-connections between simulations with time-varying forcing (Fig. 12) or fixed forcing (Fig. 11). This suggests that, at the centennial time scale, the forcing is able to mask the weak correlations associated with natural variability throughout the pre-industrial portion of the last millennium (850-1850 AD). Nevertheless, the response of the different models to the same forcing strongly varies. Some models are characterized by a very homogeneous pattern of correlation that can be both negative or positive, while some models show a more patchy pattern.

6 General discussion and conclusions

Our analysis of East Africa's hydroclimate over the last millennium is based on recent observational data, lake-based proxy reconstructions and the results of six GCMs. **When compared to recent observations (1979-2005), simulations of all models represent the unimodal seasonality of precipitation characterizing the Masoko/Malawi spatial domain rather well. The bimodal seasonality characterizing the Challa/Naivasha domain is generally less well captured by the GCMs, with a systematic underestimation of the long rains and overestimation of the short rains.** Model skill in simulating modern-day (i.e., observed)

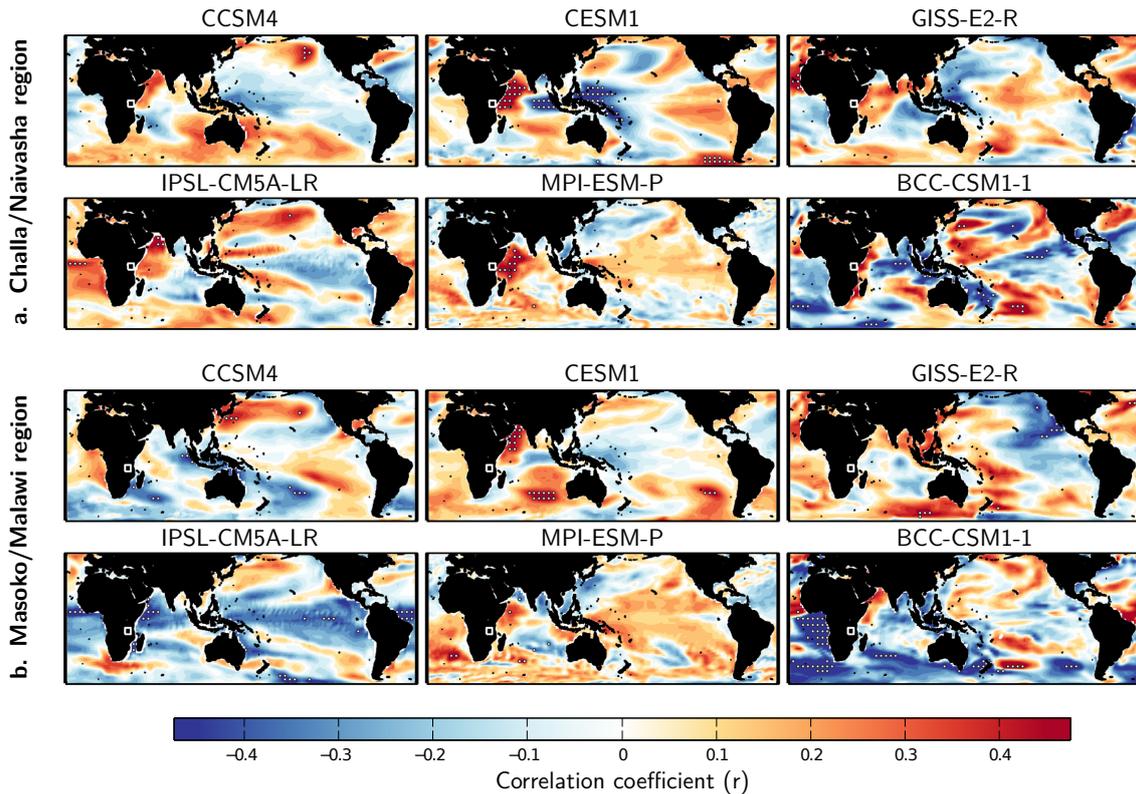


Figure 11. Pearson correlation coefficients between global SSTs and mean annual rainfall over the Challa/Naivasha (a) and Masoko/Malawi (b) regions, using the *pre-industrial control runs* of the climate models. Rainfall and SSTs are mean annual values smoothed using a loess filter with a window of 100 years. In areas overprinted by white circles the null hypothesis of no correlation can be rejected at the 5% level.

large-scale tele-connections between East African precipitation and tropical SSTs strongly varies among the GCMs, with
 25 MPI-ESM-P and CESM1 generally displaying the most consistent patterns.

Both model results and observations show that lakes Challa and Naivasha on the one hand, and Masoko and Malawi on the
 other are located in hydroclimatically relatively homogeneous regions. However, these two regions display a different rainfall
 seasonality and different large-scale tele-connections with ocean SSTs. Furthermore the lake-based proxy reconstructions from
 these two regions even show opposite moisture-balance changes during the second half of the last millennium, highlighting
 30 the strong spatial heterogeneity characterizing East African hydroclimate dynamics. Comparing the simulated variable P-E
 with the available reconstructions, we found the contribution of rainfall to be dominant relative to actual evaporation in both
 regions. Model results and reconstructions show a very different timing of hydroclimate fluctuations over the past millennium.
 Furthermore, there is no common signal among the time series modeled by different GCMs. This suggests that simulated P-E
 in East Africa is largely driven by internal variability rather than by common forcing, at least until 1850 AD. After that, half
 35 of the GCMs used simulate a relatively clear, but model-specific, response to forcing. These results are in line with those

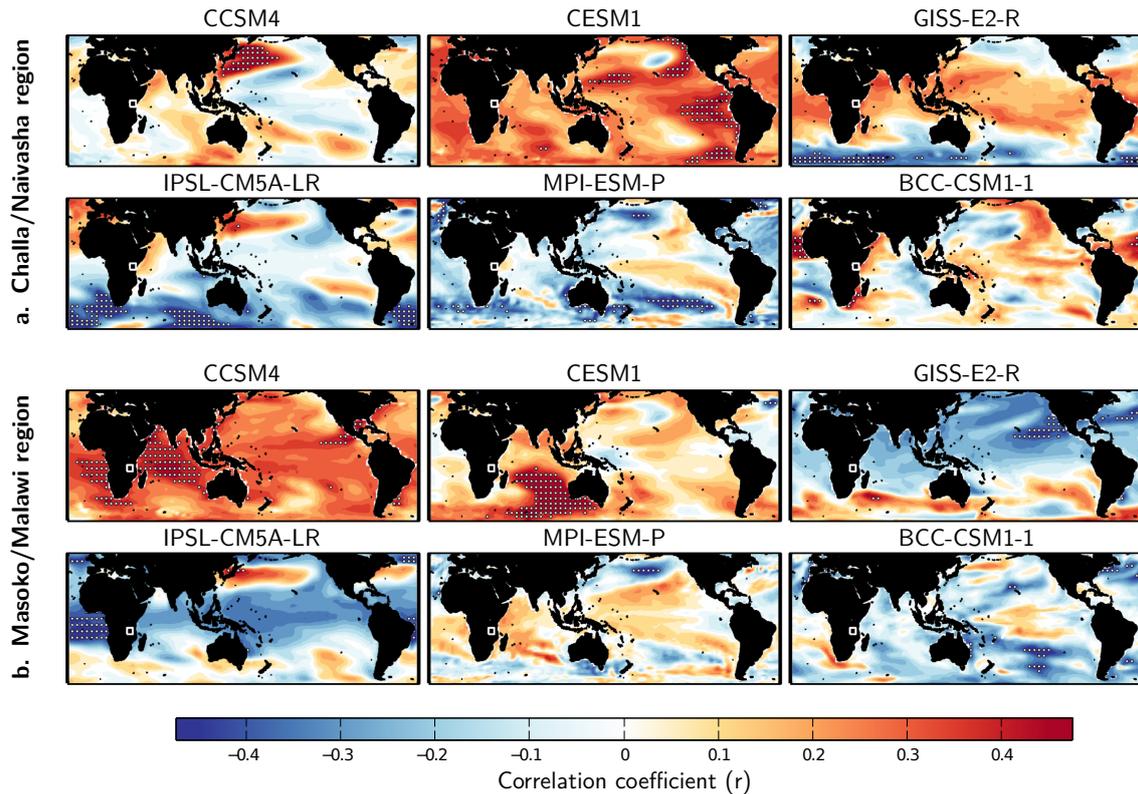


Figure 12. Pearson correlation coefficients between global SSTs and mean annual rainfall over the Challa/Naivasha (a) and Masoko/Malawi (b) regions in climate models for the pre-industrial period 850-1850 AD. Rainfall and SSTs are mean annual values smoothed using a loess filter with a window of 100 years. In areas overprinted by white circles the null hypothesis of no correlation can be rejected at the 5% level.

of Coats et al. (2015) who showed, using approximately the same set of GCMs, that multi-decadal droughts in the North American Southwest over the last millennium do not seem to be driven by external forcing. Similar conclusions were also reached by Kelley et al. (2012) who used GCMs to investigate the possibility that the late winter drying trend observed in the Mediterranean region could be explained by anthropogenic forcing. In contrast, Fallah and Cubasch (2015) suggested an impact of forcing on multi-decadal droughts in Asia over the last millennium, namely through alteration of atmosphere-ocean interactions. These contrasting results could mean that some regions are more sensitive to forcing than others.

At the inter-annual time scale, models show robust tele-connections between mean annual Indian Ocean SSTs and rainfall over the Challa/Naivasha region during the pre-industrial portion of the last millennium, with positive (negative) correlation in the western (eastern) half of the basin. The link between rainfall over the Masoko/Malawi region and SSTs is less clear among models. At this time scale, the effect of external forcing on large-scale tele-connections appears negligible. Although most of times not significant, the Indian Ocean dipole is still present using time series smoothed to highlight centennial variations, but only in fixed-forcing simulations. When taking into account the last millennium forcing, the result is completely different,

with relatively homogeneous patterns of correlation between precipitation in both regions and tropical SSTs. This means that, although the correlation pattern between Challa/Naivasha rainfall and Indian Ocean SSTs remains relatively similar for both inter-annual and centennial time scales when only natural variability is present, it is overwhelmed by the effect of forcing at the centennial time scale. An interesting question is whether the forcing actually alters the dynamical link between East African rainfall and SSTs, or if it only masks it because of a different impact on continental rainfall and SSTs. Answering this question is out of the scope of this study, but it is of interest for the interpretation of records used for reconstructing phenomena like the IOD. Indeed, if dynamical relationships are not stable when considering different time scales, a record calibrated in observations of the recent period may not be representative of the studied phenomena over longer time scales.

Analyzing an ensemble of models was particularly useful here to test the robustness of the results. Additionally, using individual models that contain several ensemble members allows attributing the simulated change to internal variability or to forcing, which is crucial in the present context of climate change in the vulnerable East African region. On the other hand, using multi-model mean results to study variation in local hydroclimate during the last millennium should be avoided. It does not make sense to average hydroclimate time series which are mostly driven by internal variability, since this would only result in concealing already weak responses.

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