

## ***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

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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 teleconnections appear to be variable over the last millennium, and between fixed forcing

C1

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

C2

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

C3

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.

C5

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-CSM1-1
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)*

C7

*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.*

C8

(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*

C9

*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-

C10

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.

C11

(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.

C12



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-

C13

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.”

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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.

C15

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

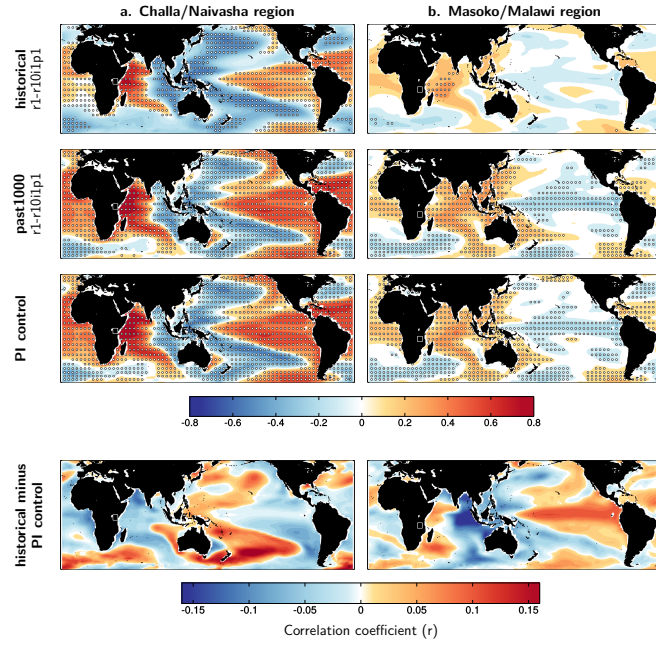
Actually, we think that this does not end on a weak note, but on a caution that can be important for future studies dealing with hydroclimate as simulated by GCMs. Furthermore, the last sentence of the previous paragraph only relates to the teleconnections, while the last paragraph is more general. We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

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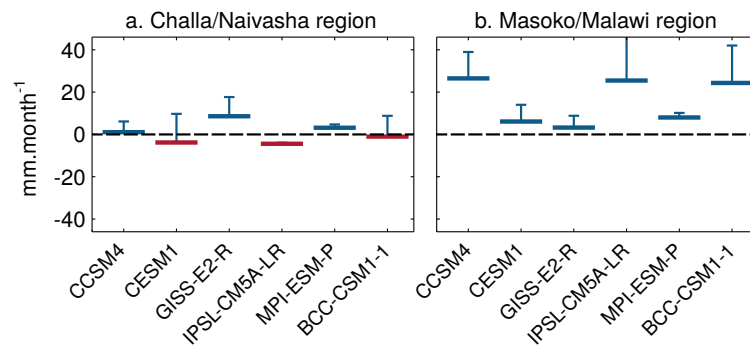




**Figure 1** – Pearson correlation coefficients between global SSTs and mean annual rainfall over the Challa/Naivasha region (left) and the Masoko/Malawi region (right), in the ‘past1000’, ‘historical’ and ‘pre-industrial (PI) control’ experiments of CESM1. For ‘past1000’ and ‘historical’ simulations (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.**

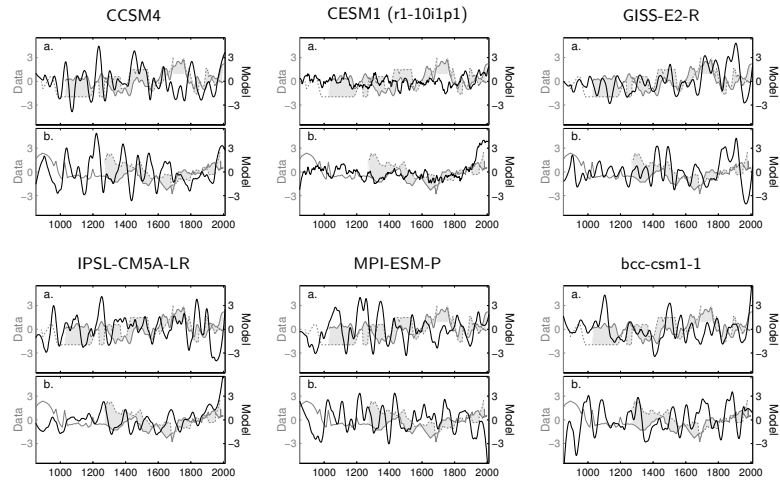
C17



**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 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.**