AUTHORS' RESPONSE TO REVIEWS OF:

Journal: HESS

Title: What are the key drivers of regional differences in the water balance on the Tibetan Plateau?

Authors: S. Biskop et al.

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We would like to thank Prof. Su for handling the review process as well as the four anonymous reviewers and S. Zhou for their valuable comments and suggestions on the manuscript. We carefully addressed all comments offered by the four reviewers and the short comment posted by S. Zhou.

In order to address some concerns raised by more than one reviewer, we start with a general response, followed by detailed responses to each reviewer. Referees/public comments are given in italic while our replies are in roman. We summarized the changes made to the manuscript in our response to the reviewers. The original manuscript is referred to as V1 and the revised manuscript as V2. Finally, we provide a manuscript version showing the changes we made to the text.

GENERAL RESPONSE #1: Research objectives

Referee #2 raised an important question: *"Which is the target of this manuscript, climatology in water balance or water balance changes?"* As indicated by remote-sensing data, lakes in the central TP experienced a continuous expansion since at least the 1970s; whereas, lakes in the southern and western TP indicated a continuous shrinkage or were relatively stable during the last decades. Lake-level changes are generally caused by a shift in the water balance. This means that most of the lakes indicated a non-equilibrium state (i.e. imbalance between input and output) already before our study period (2001-2010). Due to the time lag of lakes in responding to climatic changes and the short time period of this modeling study, we cannot prove if the shift towards a positive water balance in the Nam Co and Tangra Yumco basins or the negative shift in the water balance of the Paiku Co basin over the last decades was caused by changes in precipitation, glacier runoff, evapotranspiration, etc.

The overall objective of this study was to identify <u>differences in water-balance components</u> of closed lake basins in the south-central TP <u>during the 2001-2010 period</u>. Therefore, Nam Co and Tangra Yumco with increasing water levels (i.e. positive water balance) and Mapam Yumco and Paiku Co with stable or slightly decreasing water levels (i.e. stable or slightly negative water balance, respectively) were selected. Distributed hydrological modeling was conducted to provide i) information on spatiotemporal patterns of water-balance components (e.g., altitudinal variations, seasonal dynamics) and ii) estimates of water-balance components in order to quantify their contributions to the water balance during the 2001-2010 period (V2, P3, L17-24). From this we cannot draw definitive conclusions about the hydrological changes that have led to the imbalanced water-budget in Nam Co, Tangra Yumco and Paiku Co; however, based on our modeling results and findings of other studies we discuss potential causes for long-term lake level changes in the revised manuscript (V2, Sect. 5.1.2).

GENERAL RESPONSE #2: Title of the manuscript

As a response to these clarified research objectives and to the comment of Referee #3 that four lakes are not representative for the entire TP, we decided to change the manuscript's title to "Differences in the water-balance components of four lakes in the south-central Tibetan Plateau".

GENERAL RESPONSE #3: Structure and content of the manuscript

According to the suggestion of Referee #1, we deleted the contents of Section 4.1 "Seasonal and inter-annual variations of hydro-climatological components in the Nam Co basin" to make the paper concise.

A new Sect. 4.1 deals with model evaluation. Section 4.1.1 contains the comparison of simulated and measured lake-level of the Nam Co (as suggested by Referee #1 and S. Zhou). In Sect. 4.1.2 simulated snow-cover dynamics are compared with MODIS data for all four basins (as suggested by Referee #2).

The title of Sect. 4.2 "Regional comparative analysis of multiple lake basins" was renamed to "Comparative analysis of the four selected lake basins". The title of Sect. 4.2.1 "Spatiotemporal patterns of hydrological components" was maintained, but the content is described in more detail. The title of Sect. 4.2.2 "Regional differences in the water balance" was changed to "Contributions of the individual hydrological components to the water balance".

Section 5.1 "Comparison with other studies" in the discussion chapter was divided into two sub sections: "Estimation of the water-balance components" (Sect. 5.1.1) and "Factors controlling the water balance and lake-level variability" (Sect. 5.1.2). Section 5.2 "Limitations and uncertainties" was maintained, while Sect. 5.3 "Factors influencing long-term lake-level changes" was removed, but a large part of its content was integrated in Sect. 5.1.2.

POINT-BY-POINT RESPONSES TO ANONYMOUS REFEREE #1

SPECIFIC COMMENTS:

1. *The results are very sensitive to the initial inputs of precipitation. The most uncertainty of this study exists in the meteorological inputs of HAR10. I'm confused about the overestimation of precipitation and underestimation of lake surface temperature. As shown by Maussion et al. (2014; 2015), HAR data has been validated and published. Why there exists such overestimation or underestimation?*

   RESPONSE: No atmospheric or geophysical dataset that we are aware of can be entirely "validated". Maussion et al. (2014) compared the HAR precipitation products to station observations and TRMM estimates for the entire TP, but it is probable that the accuracy of the precipitation estimates is regionally dependent (as it is the case for global reanalyses). Maussion et al. (2014) found no systematic bias when considering all 31 stations in High Asia (their Fig. 03) but found regional differences (their Supplementary Fig. S9). Furthermore, the stations are all located in the valleys and no assessment can be done for the highest altitudes. Our manuscript is the first attempt to use HAR for hydrological modeling in the south-central TP region and as such provides a new approach to assess its uncertainty. A recent study by Pohl et al. (2015) showed that after applying a precipitation-scaling factor, HAR10 had the highest skill scores in comparison with observations in the Pamir Mountains.

   We believe to have thoroughly described and discussed the uncertainties of HAR (V1, P4281, L14-17; P4291, L21-28, and more), but we clarified these points in the revised manuscript (V2, Sect. 5.2). Other factors might play a role, such as uncertainties in the hydrological model and the omission of certain physical processes (e.g., sublimation of blowing or drifting snow) (V1, P4292, L5-15). Currently, all these uncertainties are endorsed by the precipitation-scaling factor.

   With respect to the lake-surface temperature (ST) it must be clarified that lake ST is not an output variable of HAR10 (V1, P4276, L13-19). In the WRF model version 3.3.1 (which was used for the generation of the HAR10 data), the lake ST is initialized by averaging the surrounding land-surface temperatures.

   Besides precipitation and lake surface temperature, some validation works with in-situ observation need to be done. Indeed, there are some in-situ measurements from CMA (China Meteorological Administration) or CAS (Chinese Academy of Sciences) over the TP.

   RESPONSE: The comparison of the HAR10 temperature data with in-situ measurements indicated that the HAR10 temperatures in the summer months are closer to ground observations than in winter (Maussion, 2014). However, despite the winter cold bias, the overall seasonality is well reproduced (Maussion, 2014). The cold bias effect on the accuracy of the hydrologic-modeling results is assumed to be low, because hydrological processes governing lake-level changes are more critical during the other three seasons of the year (V2, P5, L18-22).

   Meteorological data from an automatic weather station installed on the Zhadang glacier in the Nam Co basin was used to validate HAR10 data in high altitude glacierized environments. The results show that air temperature, relative humidity and wind speed from HAR10 are in accordance with observations (Maussion, 2014; Mölg et al., 2014; Huintjes et al., 2015)

2. *It’s not proper to use a fixed precipitation-scaling factor for the whole study period.*

   RESPONSE: Unfortunately, we are not sure to understand if the reviewer means different precipitation-scaling factors for single years? We agree with Referee#1's concern about using a fixed precipitation-scaling factor as pointed out in the original manuscript (V1, P4292, L2-4). However, there is no opportunity to derive varying scaling factors for single years for the four studied lake basins due to the lack of observations.

   Is it possible to tell the scientific community what are the main water vapour sources of increasing precipitation in Nam Co. Is it mainly from the plateau itself or surrounding regions?

   RESPONSE: This is a very important question which is still under debate and will probably stay so in the close future. Recent efforts concentrated on quantifying the water vapor input to the Plateau (Feng and Zhou, 2012, Curio et al., 2015), but both studies did not focus on the water transport changes.

   Feng, L. and Zhou, T.: Water vapor transport for summer precipitation over the Tibetan Plateau: Multidata set analysis, Journal of Geophysical Research, 117, D20, 1-16, 2012.

   Curio, J., Maussion, F., and Scherer, D.: A twelve-year high-resolution climatology of atmospheric water transport on the Tibetan Plateau, Earth System Dynamics, 6, 109-124, 2015.

3. *As shown by section 5.2, there are many uncertainties about this study. Therefore, what we get should be a variation range rather than some specific values listed in Table 4.*

   RESPONSE: The precipitation-scaling factor was found to be the most sensitive parameter with the highest impact on model results. To provide a variation range of several water balance components, the results of the model runs with precipitation-scaling factors ±0.05 with regard to the reference run were added to Table 4.

4. *Some in-situ measurements may help to reduce the uncertainties. To my knowledge, there is a comprehensive station in the Nam Co basin constructed by CAS. Some hydrological and meteorological observations can be achieved to make some validation work for your model outputs.*

   RESPONSE: Lake-level observations from 2006 to 2010 provided by the ITP/CAS were used for model validation. However, lake level values during the freezing (wintertime) periods are missing, because the lake level gauge was destroyed by lake ice, and therefore, rendered inoperable each winter. Thus, data is only available for the ice-free period (May/June – November/December). The lake-level measurements began again each spring, but, unfortunately, an absolute lake level was not measured. As a result, the lake-level observation data contain an unknown shift between the consecutive years (V2, P6, L15-21; Sect. 4.1.1, Fig. 3).

TECHNICAL CORRECTIONS:

1. *The paper only focused on four typical closed basins. The title should be specific. It’s better to be replaced by ‘What are the key drivers of regional differences in the water balance of four lakes on the Tibetan Plateau?’*

RESPONSE: The title was replaced (see general response #2).

2. *The contents of section 4.1 should be deleted to make the paper concise.*

   RESPONSE: Done. See also general response #3.

3. *P4274, L1, 'Cuo et al., 2014' should be corrected as 'Lan et al., 2014'. Similar correction should be done at P4297, L15.*

   RESPONSE: We are a bit confused, because we checked the first and the last name. We could find other publications from L. Cuo (for example in the reference list from the paper stated above), but we could not find a publication from C. Lan. Thus, we did not change 'Cuo et al., 2014' to 'Lan et al., 2014'.

   P4291, L1, 'Li, B. et al. (2014)' should be replaced by 'Li et al. (2014)'.

   RESPONSE: The initial of the first name was added by Copernicus Publications Production Office to distinguish between references with the same last name and the same year. See also V1, P4274, L3.

POINT-BY-POINT RESPONSES TO ANONYMOUS REFEREE #2

MAJOR COMMENTS:

1. *The title and main point of this manuscript is the regional differences in the water balance among four lakes. Precipitation from HAR is post-processed by a precipitation scaling factor due to the overestimation in HAR. However, fixed factors are adopted for the four lakes and the results were used to analyze the causes of the regional differences in the water balance. This does not make sense. Given the predominant role of precipitation in the hydrological simulation, the scaling factor will has influence not only on the ratio of snow (glacial) melt and precipitation contribution in runoff at single point simulation; but also the spatial distribution among four lakes would be influenced greatly.*

   RESPONSE: We agree that the adaption of HAR10 precipitation for each lake basin investigated in this study consequently raises issues about the reliability of the model results. However, due to the fact that errors in HAR10 precipitation probable vary regionally, there is no precipitation-scaling factor which is valid and applicable for the entire HAR10 domain. HAR10 data has been successfully used in glaciological modeling studies on the TP (Huintjes, 2014; Mölg et al., 2014; Huintjes et al., 2015) and recently in a hydrological modeling study in the Pamir Mountains (Pohl et al., 2015), but with the need to apply a precipitation-scaling factor < 1 in all studies. The values of the precipitation-scaling factor vary enormously among the serval studies, from 0.37 in the Pamir Mountains (Pohl et al., 2015) to 0.79 in central TP (Mölg et al., 2014). Due to the scarcity of observation data and the difficulty to obtain meaningful correction factors from comparison with in-situ data, the only viable way to derive a precipitation-scaling factor is the evaluation of modeled hydrological quantities (Pohl et al., 2015). For the Zhadang glacier in the Nam Co basin, Mölg et al. (2014) found a very good agreement between glacier mass-balance model calculations and available in-situ measurements by applying a precipitation-scaling factor of 0.79. This value is relatively close to the precipitation-scaling factors obtained for the Nam Co (0.80), Tangra Yumco (0.75) and Paiku Co (0.85) basins by comparing modeled and satellite-derived lake-volume changes. This gives us confidence that the scaling factors used in our study seemed to be in an acceptable range (V2, Sect. 5.2).

   The relatively low precipitation-scaling factor of 0.50 obtained for the Mapam Yumco basin seems to be plausible when comparing HAR10 precipitation with weather station data of Burang (30°17’N, 81°15’E, ~30 km to the south, closest station with available data) published in Liao et al. (2013). Huintjes (2014) also found that a reduction of the precipitation by more than 50 % leads to more reliable mass-balance results for the Naimona’nyi glacier (Gurla Mandhata, south western TP) which is located close to the Mapam Yumco basin. As the precipitation-scaling factor can compensate model-structure inadequacies, in particular wind-induced sublimation of suspended snow, the low value of 0.5 applied in the Mapam Yumco basin and the even lower value of 0.37 used in study of Pohl et al. (2015) might be an indication that this process plays a major role in regions which are stronger influenced by Westerlies (V2, Sect. 5.2).

   At this moment, unfortunately, we have no other possibility than to use a scaling factor, in order to account for judged effective precipitation. Having said that, we think the different scaling factors do not affect the overall conclusions drawn from the hydrological modeling. We strongly believe that our model results contribute to a better understanding of the factors controlling the water balance and lake-level variability in the four studied lake basins.

2. *Concepts of the climatology and change are kind confused. Which is the target of this manuscript, climatology in water balance or water balance changes? It seems authors refer to the precipitation is the key drivers in the runoff climatology because of the small proportion glacial there. For instance, it says glacial runoff is small due to small glacial coverage in section 4.1. It is self-evident. However, what interested are key drivers of runoff changes response to warming. Unfortunately, not much evidence of relative changes in precipitation, and glacial runoff are demonstrated. In Figure 3a (right), there almost no trend in precipitation in 2001-2010; however, warming is obvious. So, the rising in the lake table in Table 4 should attributes to the glacial runoff change due to warming. Accordingly, the water-balance components in the upper part of Table 4 show relative changes in the water balance components rather than values of ten years climatology. It is kind misleading.*

   RESPONSE: Thanks for rising this important point. We hope we could make our research objectives more clearly in general response #1 and in the revised manuscript. Furthermore, we clarified the conclusions drawn from the modeling results to avoid the Referee#2's misunderstanding that "[…] precipitation is the key drivers in the runoff climatology because of the small proportion glacial there."

   We do not think that the 10-year study period can allow us to reach conclusions about <u>runoff trends</u> in the studied basins due to warming. As pointed out in the general response #1, there was already an imbalance between input and output prior to the study period. Thus, we cannot answer the question which factors have led to the shift in the water balance. To our knowledge, there is no general agreement about the reasons for lake-level increases on the Plateau (e.g., Li et al., 2014), which might have complex causes (precipitation, evapotranspiration, glacier melt, permafrost degradation, etc.) (see our discussion in V2, Sect. 5.1.2). Moreover, we conducted an ice-free scenario for all basins to better understand the role of glacier runoff during the study period (V2, P15, L9-21).

   The upper part of Table 4 summarizes mean annual estimates of water-balance components and no relative changes. The table heading was clarified to avoid misleading.

3. *As mentioned above, there almost no trends in precipitation in 2001-2010 letting alone the significance test. So, it is not convincing saying precipitation changes are the key drivers of the lake level in such short period. Some previous studies reported a long term lake level changes in recent decades (Yang et al. 2011; Lei et al. 2014). It was demonstrated that the lake level changes are consistent with P-E changes over the Tibetan (Gao et al. 2015).*

   RESPONSE: Unfortunately, this is also a misunderstanding (see response above). We hope that we could clarify the parts in the revised manuscript that have led to this misunderstanding. Long-term lake-level changes are discussed in V2, Sect. 5.1.2.

4. *To show the difference from Mölg et al. (2014), suggest changing title as "What are the key drivers... Tibetan Plateau, precipitation or glacial melt?" or "What are the key surface drivers...?"*

   RESPONSE: Title was changed (see general response #2).

5. *P4276 L20-29, why not use the consistent MOD11A2 land-surface temperature products for four lakes? The same as other land characteristics (land cover). These differences could lead to differences in four lake simulation. How these results could be used in regional differences.*

   RESPONSE: We preferably used the lake-surface water temperature (LSWT) observations from the ARC-Lake v2.0 data product as input for the estimation of long-wave radiation over water surface, because this data set does not contain outliers like MOD11A2 land-surface temperature data and no correction was required as in the case of MODIS. However, unfortunately, there are no ARC-Lake data for Paiku Co and Mapam Yumco and hence the MOD11A2 land-surface temperature data product was used (V1, P4276, L20-28). We compared daily ARC-Lake and MOD11A2 data for the Nam Co and found a very good agreement (r = 0.99, deviation between annual means: 0.01°C). Moreover, the model run with MOD11A2 had not led to any significant change that could influence our outcomes.

   Furthermore, we found that land-cover classification data used in this study (they are all based on Landsat data – 30 m resolution) are more accurate than the globally available data sets (MODIS – 500 m resolution, GlobCover – 300 m resolution) in comparison to ground-truth data. Thus, we believe that the Landsat-based land-cover classifications are a better choice than a global land-cover data set.

6. *P4277, MODIS snow cover are used for validation of the snow modeling in the Nam Co basin. Why not do the same validation for other three basins?*

   RESPONSE: We now use MODIS snow-cover data for validation of the snow modeling in all basins (V2, Sect. 4.1.2, Fig. 4).

7. *P4278, non-glacial runoff is generated by snowmelt and rainfall. Glacier runoff is generated by snow and ice melt. There is also rainfall over the glacial area. And, snow usually covers over the glacial area. So, the definition sounds not reasonable.*

   RESPONSE: The sum of snowmelt, ice melt and rain over glaciers is defined as glacier runoff in the model. The definition of glacier runoff was corrected in the revised manuscript.

8. *P4285 L9-25, impervious layers might play a role.*

   RESPONSE: We are not sure to understand if the reviewer means impervious layers caused by the occurrence of permafrost. Unfortunately, we have no information about permafrost layers in the studied lake basins and thus the effect of impervious layers on altitudinal variations of runoff cannot be analyzed with the model. We added a discussion sentence about permafrost in Sect. 5.1.2.

POINT-BY-POINT RESPONSES TO ANONYMOUS REFEREE #3

SPECIFIC COMMENTS:

1. *Four closed lake catchments in the south-central part of Tibet cannot be representative for the whole Tibetan Plateau. As reported in (Zhisheng et al, 2001; Tao et al., 2004; Yao et al., 2012), temperature, humidity and precipitation differently occur at different parts of the Tibetan Plateau. This makes it likely that different patterns of glacial changes and water level changes occur at different parts of the Tibetan Plateau. Maybe these four lake catchments could belong to the same pattern because of their locations.*

   RESPONSE: We agree with the referee. As stated in general response #1 and #2, the revised manuscript now focuses on four selected lakes across the south-central TP and not on different regional patterns any more.

2. *Analyzing spatiotemporal patterns of water balance components seem to have been forgotten to describe in this manuscript. Four lake catchments are not enough to analyze a spatial statistics problem to determine a correlation of the water-balance components in different parts of the Tibetan Plateau. Furthermore, the water mass change of one or two lake catchments is not representative for a regional pattern.*

   RESPONSE: We agree with the referee.

3. *Quantifying single water-balance components and their contribution to the water balance of a closed lake catchment was estimated by using the water mass balance modelling J2000g. In this paper, the authors applied it to four lake catchments, including the Nam Co catchment (Krause et al., 2010). What factors are improved in methodology?*

   RESPONSE: In the previous modeling study of the Nam Co basin (Krause et al., 2010) coarse gridded climate data with a resolution of 50 km had to be used as input, due to a lack of climate data. In the present study, the model is driven by the new higher resolved HAR10 data (10 km). In the present study, lake-surface temperatures either provided by the ARC-Lake data or derived from MODIS data were used as additionally data inputs for the estimation of the long-wave radiation term over the lake surface. In the earlier study of Krause et al. (2010), a simple catchment distribution with coarse modeling entities was used; whereas, a finer spatial discretization based on the traditional HRU-concept was applied for this modeling approach.

   Moreover, model adaptions and process implementations have been performed to enhance the representation of processes, with particular importance for the study area (see also the supplementary material). The long-wave radiation part of the FAO56 calculation was modified according to the recommendations of Yin et al. (2008) (V1, P4279, L24-25). In the standard radiation module of JAMS, there is no distinction between the calculations for the net long-wave radiation for land versus water surfaces. Due to the fact that the exchange of radiant energy between the lake surface and the atmosphere in the form of long-wave (thermal) radiation is significant for large lakes, a new component for the calculation of the net long-wave radiation over lakes that takes into account water-surface temperature was implemented in JAMS (V1, P4279, L25-27). For the estimation of open-water evaporation rates from large lakes, the Penman equation modified by the addition of the lake heat-storage was used. As suggested by Valiantzas (2006), the reduced wind function proposed by Linacre (1993) was applied for the estimation of evaporation from large open-water body surfaces (V1, P4279, L27-29 –P4280, L2-3).

Within JAMS, the user can choose between a snowmelt module based on a simple day-degree approach (implemented in J2000g and used in Krause et al., 2010) or a more complex calculation method (implemented in J2000) that is principally following the approach developed by Knauf (1980). Due to the high importance of the refreezing process in the snow pack in the study region, the latter module that combines empirical or conceptual approaches with more physically-based routines was selected for this study (V1, P4280, L2-4).

Here, the topic focuses on the water mass balance of a closed catchment, so the authors should represent a temporal relation of water-balance components rather than that of climatic parameters during the observed period.

RESPONSE: We are not sure to fully understand this comment. If the referee means Figure 6 in the original manuscript (V1), the focus was on climate forcing in order to illustrate that inter-annual variations in lake evaporation are related to specific combinations of climatic parameters in individual years. However, this figure was removed, because the contents of Sect. 4.1 in the original manuscript (V1) were deleted (see general response #3). In Figure 5 and 7 in the revised manuscript (V2) we show seasonal and inter-annual variations of several water-balance components.

POINT-BY-POINT RESPONSES TO ANONYMOUS REFEREE #4

MAIN COMMENTS:

1. Better highlight the transient character of current hydrological system due to net glacier mass loss. The authors identify high correlations of annual lake volume changes with land runoff and precipitation.

No correlations were found between annual glacier melt amounts and lake-volume changes in the four basins. The modeled relative contribution of glacier runoff to total water inflow was between 15 and 30%, from which the authors conclude that glacier runoff plays a minor role, compared to precipitation and snowmelt runoff, for the water balance on the TP (P. 4295, lines 1-5). They also conclude from those results that 'the positive water balance in the Nam Co and Tangra Yumco basins was caused by higher precipitation totals' (P. 4295, lines 7-9). However, I do not fully agree with this assessment. Figure 5 shows that glaciers in the Nam Co basin are not in a balance with the current climate since glacier runoff exceeds precipitation in the corresponding elevation bands of the basin by far. This means that current glacier runoff is largely due to net glacier mass loss, which is however not a sustainable source of runoff which will disappear once the glaciers reach a new equilibrium with the climate (after strong glacial retreat, identified e.g. by Yao et al. 2007). The authors should therefore make very clear if the water balance in the Nam Co and Tangra Yumco basins would still be positive without glacier runoff originating from net glacier mass loss. If not, this would substantially affect the conclusions that can be drawn from this study since glacier runoff would indeed be potentially the main driver of net lake level increases.

RESPONSE: Thanks for raising this important point. Now we present a hypothetical scenario with ice-free conditions for each lake basin in order to clarify the importance of ice-melt runoff for the mean annual water balance (2001-2010) (V2, P15, L9-21). We think that this strengthens the discussion about the role of glaciers.

2. Provide a better documentation of past lake area changes. As the authors state correctly the time lag in the response of the area of a closed lake to climate fluctuations depends on the geomorphological characteristics of the lake: 'the higher the rate of change of a given lake's area with volume, the faster the lake can adjust its area' (P. 4294, lines 16-17). The authors should therefore try to document past lake area changes in the four basins in order to understand if the differences in lake level changes are not simply due to differences in the lake response times.

RESPONSE: Thank you for providing this idea. We considered past lake area changes in the new discussion section (V2, Sect. 5.1.2).

3. Permafrost degradation

Permafrost degradation induced by rising temperature has been identified as another potential driver of lake level changes (e.g. Li et al., 2014). The authors should consider this at least in their discussion.

RESPONSE: This is another good point. However, as discussed in the revised manuscript (V2, Sect. 5.1.2) permafrost degradation cannot be considered in the model at this state.

DETAILED COMMENTS

- *P. 4272, line 25: observational data 'are' missing*

  RESPONSE: Done.

- *P. 4276, line 12: Please also state which temporal resolution is used.*

  RESPONSE: Done.

- *P. 4277, line 22 ('are close to the changes rates estimated by. . . '): Please provide the numbers in the text as well and not only (subjective) qualitative measures.*

  RESPONSE: Done.

- *P. 4278, line 11 ('The J2000g model is a simplified version. . .'): Please be more specific in which respect the model is simplified.*

  RESPONSE: Done.

- *P. 4278, from line 23 ('the net water budget . . . was estimated by'): Evapotranspiration should also appear here.*

  RESPONSE: Evapotranspiration is now included in the model description (V2, P9, L5-7).

- *P. 4279, from line 10: which are the 'new model modules' which were required for representing the 'specific characteristics of closed lake basins on the TP'? Please be more specific.*

  RESPONSE: Done.

- *P. 4279, line 21 ('were regionalized using only IDW'): you can remove the 'only'.*

  RESPONSE: This sentence was completely removed.

- *P. 4280, lines 17-23 ('In the absence of. . .'): This seems rather obvious. Consider to shorten this paragraph.*

  RESPONSE: Done.

- *P. 4282, line 15: 1 mm SWE seems a very low threshold for detection by MODIS. For comparison with MODIS I suggest testing higher thresholds. Gascoin et al. (2015) estimate the values of best detection thresholds to as high as 40 mm SWE. This could also explain the significant overestimation of snow cover by the model (P. 4283, line 24).*

  RESPONSE: We tested different thresholds (SWE > 1, 10, 50 mm) (V2, P11, L12-14). The results are presented in V2, Sect. 4.1.2, Fig. 4.

- *P. 4283, line 22: Please report already in the 'Methods' section that sublimation is a process which is taken into account by the model explicitly (and not only through the precipitation correction factor).*

  RESPONSE: Done.

- *P. 4285, line 10 ('spatially distributed pattern'): I suggest replacing 'distributed' by 'heterogeneous'.*

  RESPONSE: Done.

- *P. 4288, lines 6-8 ('The relation between. . .'): This is a repetition and also rather obvious. You can remove this sentence.*

  RESPONSE: Done.

- *P. 4288, line 16 (and elsewhere, e.g. line 22 same page): The authors write contribution of glacier melt was 'only' 14%. However, in comparison to the percent glacier area to total glacier area this is a lot. I would therefore hesitate to say 'only'. See my major comment 1 above.*

  RESPONSE: We agree with the referee and considered it in the revised manuscript.

- *P. 4289, line 26 ('Our results are within this range (Table 4)'): Please report the values also in the text.*

  RESPONSE: Done.

- *P. 4290, lines 20- 29: For this comparison it would be useful to know how the SEB/MB models for Zhadang glacier were evaluated.*

  RESPONSE: Simulated glacier-mass balance estimates were validated against in-situ measurements.

- *P. 4293, lines 6-7 ('errors in the satellite-derived water volume data'): Is it possible to quantify the mean error in order to provide an uncertainty range?*

  RESPONSE: Unfortunately, there is no information on errors in the satellite-derived water-volume data that could be used to provide an uncertainty range.

- *P. 4293, lines 12-13 ('Therefore, model outputs might also be influenced. . .'): This is obvious. Remove or change this sentence.*

  RESPONSE: We removed this sentence.

- *P. 4293, lines 19-28: it should be stated somewhere which results the nonconsideration of lake groundwater interactions could affect. Likely this would only affect the seasonal variability of the modelled lake level and not the multi-annual changes.*

  RESPONSE: It would basically have a dampening effect on the seasonal lake level, because of an additional storage, which is not considered by the model. That means that the amplitudes can be overestimated. In terms of multi-annual changes, we think that the effect can be neglected (V2, P23, L1-3).

  To which time scale apply the ranges of relative contribution of exfiltration/infiltration reported here?

  RESPONSE: Annual lake-water budgets.

RESPONSE TO SHORT COMMENT POSTED BY S. ZHOU

I mainly looked at the results of Lake Nam Co. I appreciate their work and agree with them that the key driver is the precipitation. However, I found large differences between their simulated results and the in-situ observations of most components of the lake water balance. Of the four lakes, Nam Co is the only lake with detailed longterm in-situ observations of lake water balance (Zhou et al., 2013). I wonder that, while they cited the paper by Zhou et al. (2013), they did not refer to it. So I would suggest the authors to compare their results with the observed data by Zhou et al. (2013). In addition, possible water seepage of the lakes could be taken into consideration. I would like to provide some important information: In-situ observations show that the average annual lake level increase of Lake Nam Co was only several centimeters during the period of 2005-2010 (unpublished yet), much lower than the data they adopted (22 cm per year, Table 2). Also, the precipitation was around 340 mm at Nam Co Station during the period from July through December 2006, which is much higher than their data of 270 mm for the whole year (P4283, Line 13).

RESPONSE: We thank S. Zhou for the kind words about our work. As mentioned previously, consistent lake-level measurements from Nam Co are only available for the ice-free period from the years 2006-2010. For the year 2005 we have only 30 values between the end of August and the beginning of November. Due to the lag of continuous lake-level measurements in the studied basins, we used satellite-derived lake-volume changes to calibrate the overall system response (i.e. lake-volume change). Thus, a possible inaccurate mean annual lake-level change obtained from the model could be related to errors in the satellite-derived lake-volume change. Due to an unknown shift between the consecutive years, we are not able to compare modeled multi-annual lake-level changes with in-situ measurements. So, we are wondering how an average annual lake-level change during the 2005-2010 period (unpublished yet) could be estimated without continuous time series. Moreover, it should be note that the modeled mean annual lake-level increase relates to the period 2001-2010, while S. Zhou refers only to the 2005-2010 period. It is difficult to compare mean annual lake-level changes from different time periods.

Because of the unknown shift between consecutive years, we compared simulated and measured lake levels only for single years (V2, Sect. 4.1.1). Due to the large data gaps in 2005, we did not include the year 2005 in this comparison. The comparison revealed that the simulated mean monthly lake levels agree well with the measurements ($r = 0.81$). However, the modeled lake level indicates a non-systematic pattern compared to the measurements which might be related to errors in HAR10 precipitation (V2, Sect. 4.1.1; V2, P20; L29-31). Specifically, the model underestimates significantly the observed lake level in 2006 (V2, Fig. 3). This is likely due to a precipitation underestimation, which fits with the finding of S. Zhou that the precipitation measured at the Nam Co station was higher than HAR10 precipitation in this specific year. A possible HAR10 precipitation underestimation in 2006 would be increased due to the application of a fixed precipitation-scaling factor of 0.8. As already discussed above, there is no opportunity to derive varying scaling factors for single years. However, we believe that uncertainties which appear to be related to the precipitation-scaling factor, should not affect the overall conclusions drawn from the model results.

Possible water seepage of the lakes is addressed in V2, Sect. 5.1.2.

Minor comments: P4284, Lines 11-13: The main reason should be the lower air temperature caused by more precipitation during the melt season (Zhou et al., 2010).

RESPONSE: The contents of Section 4.1 were deleted as suggested by Referee #1 (see also general response #3).

~~What are the key drivers of regional differences in the water balance on the Tibetan Plateau?~~Differences in the water-balance components of four lakes in the south-central Tibetan Plateau

S. Biskop[1], F. Maussion[2], P. Krause[3] and M. Fink[1]

[1]{Department of Geography, Friedrich Schiller University Jena, Germany}

[2]{Institute of Meteorology and Geophysics, University of Innsbruck, Austria}

[3]{Thuringian State Institute for Environment and Geology, Jena, Germany}

Correspondence to: S. Biskop (sophie.biskop@uni-jena.de)

Abstract

~~Lake level fluctuations in closed basins on the Tibetan Plateau (TP) indicate climate-induced changes in the regional water balance.~~ The contrasting patterns of lake-level fluctuations across the Tibetan Plateau (TP) are indicators for differences in the water balance over the TP. However, little is known about the ~~region's~~ key hydrological ~~parameters, hampering the interpretation of these changes~~factors controlling this variability. The purpose of this study is to contribute to a more quantitative understanding of these ~~controls~~factors~~. Four~~ for four selected lakes in the south-central part of the TP~~ were selected to analyze the spatiotemporal variations of water-balance components~~: Nam Co and Tangra Yumco (~~indicating~~ increasing water levels), and Mapam Yumco and Paiku Co (~~indicating~~ stable or slightly decreasing water levels). We present the results of an integrated approach combining hydrological modeling, atmospheric~~-~~ model output and remote-sensing data. The hydrological model J2000g was adapted and extended according to the specific characteristics of closed~~-~~-lake basins on the TP and driven with “High Asia Refined analysis~~”~~ (HAR)” data at 10 km resolution for the period 2001-2010. ~~Our results reveal that because of the small portion of glacier areas (1 to 7 % of the total basin area) the contribution of glacier melt water accounts for only 14-30 % of total runoff during the study period. Precipitation is found to be the principal factor controlling the water balance in the four studied basins. The positive water balance in the Nam Co and~~

~~Tangra Yumco basins was primarily related to larger precipitation amounts and thus higher runoff rates in comparison with the Paiku Co and Mapam Yumco basins.~~ Differences in the mean annual water balance among the four basins are primarily related to higher precipitation totals and attributed runoff generation in the Nam Co and Tangra Yumco basins. Precipitation and associated runoff are the main driving forces for inter-annual lake variations. The glacier-meltwater contribution to the total basin runoff volume (between 14 and 30 % averaged over the 10-year period) plays a less important role compared to runoff generation from rainfall and snowmelt on non-glacierized land areas. Nevertheless, using a hypothetical ice-free scenario in the hydrological model we indicate that ice-melt water constitutes an important water-supply component for the Mapam Yumco and Paiku Co, in order to maintain a state close to equilibrium; whereas, the water balance in the Nam Co and Tangra Yumco basins remains positive under ice-free conditions. ~~This study~~These results highlight~~s~~ the benefits of ~~combining~~ linking ~~atmospheric and~~ hydrological modeling with atmospheric-model output and satellite-derived data~~.~~, and ~~T~~the presented approach can be readily transferred to other ~~ungauged~~ data-scarce closed lake basins ~~on the TP~~, opening new directions of research. Future work should go towards ~~increasing the atmospheric model's spatial resolution and toward~~ a better assessment of the model-chain uncertainties, especially in this region where observational data ~~is missing~~ are scarce.

1 Introduction

The drainage system of the interior Tibetan Plateau (TP) is characterized by numerous closed- ~~(endorheic)~~ lake (endorheic) basins. Because an endorheic lake basin integrates all hydrological processes in a catchment, lake-level or volume changes provide a cumulative indicator of the basin-scale water balance. While most of the lakes located in the central part of the TP are characterized by a water-level increase over recent decades (e.g., Zhang, et al. 2011; Phan et al., 2012), there are also several lakes with nearly stable or slightly decreasing water levels in the southern part of the TP. These high-elevation lakes are therefore considered to be one of the most sensitive indicators for regional differences in the water balance ~~on~~ in the TP region (e.g., Zhang, B. et al., 2013; Zhang, G. et al., 2013; Song et al., 2014).

Neglecting the influence of long-term storage changes such as deep groundwater and lake-groundwater exchange, the net water balance of an endorheic lake basin with water supply from glaciers can be expressed as: $\Delta V_{lake} = P_{lake} - E_{lake} + R_{land} + R_{glacier}$, where ΔV_{lake} is the lake-volume change (net annual lake-water storage), P_{lake} the on-lake precipitation, E_{lake} the evaporation rate from the lake, and R_{land} and $R_{glacier}$ are the runoff from non-glacierized land surface and from glaciers (in units of volume per unit time). Under constant climatic conditions, endorheic lakes will eventually tend towards a stable equilibrium ($\Delta V_{lake} = 0$), where the several water-balance terms are balanced (Mason, 1994). Lake-level changes thus result from a shift in the water input or output.

Due to the accelerated glacier mass loss, it has been hypothesized that lake-level increases are primarily due to an increased inflow of glacier melt water (e.g., Yao et al., 2007; Meng et al., 2012). Nevertheless, glacier runoff into lakes itself should not increase the overall water-volume mass ~~on~~ in the TP, ~~based upon~~ as indicated by ~~the~~ GRACE satellite gravimetry data (Zhang, G. et al., 2013). Furthermore, numerous lakes of the TP are not linked to glaciers (Phan et al., 2013), and the water-level changes of lakes without glacier meltwater supply in the 2000s were as high as those of glacier-fed lakes (Song et al., 2014). In other studies, increased precipitation and decreased evaporation were generally considered to be the principal factors causing the rapid lake-level increases (e.g., Morrill, 2004; Lei et al., 2013; 2014). Li, Y. et al. (2014) argued for the importance of permafrost degradation on recent lake-level changes. ~~However, potential evaporation has tended to increase, especially in the inner Plateau, during the last decade (e.g., Yin et al., 2013).~~ Thus, recent studies addressing the controlling mechanism of lake-level fluctuations remain controversial. ~~This raises the question: What are the key drivers of regional differences in the water balance on the TP?~~

~~To answer this question, knowledge of spatiotemporal variations of several water-balance components and their contribution to the basin water balance is needed.~~

In order to explore differences in the water balance of endorheic lake basins in the TP region, ~~Some~~ recent studies emphasize the urgency of the quantification of water-balance components by using hydrological models (e.g., Cuo et al., 2014; Lei et al., 2014; Song et al., 2014). ~~However, previous studies primarily rely on simplified water-balance calculations (e.g., Zhu et al., 2010; Zhou et al., 2013; Li et al., 2014b).~~ Hydrological modeling studies of endorheic lake basins in the TP region are rare ~~on the TP~~ (e.g., Krause et al., 2010), principally due to a lack of hydro-climatological observations and limitations in spatial and temporal coverage of available gridded climate data (Biskop et al., 2012). The paucity of spatial information of climatological variables was addressed by Maussion et al. (2014) ~~by developing~~ who developed a high resolution (up to 10 km x 10 km) atmospheric data set for the 2001–2011 period, the "High Asia Refined analysis (HAR)". The HAR10 data set was successfully applied in surface energy balance/mass balance (SEB/MB) modeling studies (~~Huintjes, 2014;~~ Mölg et al., 2014~~)~~; Huintjes et al., 2015) and in a hydrological modeling study in the Pamir Mountains (Pohl et al., 2015), but has not yet been used as input for catchment-scale hydrological modeling studies ~~on~~ in the central TP. The objective of this study is the hydrological modeling ~~and system analysis~~ of ~~glacierized~~ endorheic lake basins ~~along a lake transect~~ across the southern-central part of the TP in order to:

i) analyze spatiotemporal patterns of water-balance components and to contribute to a better understanding of their controlling factors,

ii) quantify single water-balance components and their contribution to the water balance, and obtain a quantitative knowledge of the ~~components~~ key factors governing the water-~~ ~~balance ~~changes~~ and lake-level variability during the 2001-2010 period~~at a catchment to regional scale~~.

~~To our knowledge, this is the first hydrological study applying a distributed, process-oriented model in multiple lake basins on the TP. The Nam Co basin was chosen as starting point for the modeling approach applied in this study, because it is the basin with the best hydrological data availability. The Tangra Yumco, Paiku Co and Mapam Yumco basins (Fig. 1) were included in this study for the transfer of the hydrological model.~~ The lakes Nam Co and Tangra Yumco with increasing water levels (i.e. positive water balance) and the lakes Mapam Yumco and Paiku Co with stable or slightly decreasing water levels (i.e. stable or slightly negative water balance, respectively) were selected to investigate differences in the water-balance components. The paper is organized as follows. In Sect. 2, we describe the study area and the data used. Section 3 gives details of the hydrological modeling approach and in Sect. 4, we present the modeling results and asses similarities and differences among the basins; in Sect. 5, the results~~,~~ limitations and uncertainties of this study are discussed with respect to findings from other studies~~, sources of modeling uncertainties and factors influencing long-term lake-level changes~~. Finally, Sect. 6 highlights the principal results and concludes with remarks on future research needs and potential future model applications.

2 Study area and data

2.1 Description of the study area

The study region comprises four closed lake basins along a west-east (W-E) lake transect in the south-central part of the TP between 28°N~32°N and 81°E~92°E (Fig. 1). Basic characteristics of the selected lake basins are summarized in Table 1. Climatologically, the study region encompasses a semi-arid zone and is characterized by two distinct seasons: a temperate-wet summer season dominated by the Indian Monsoon and a cold-dry winter season determined by the Westerlies. The mean annual air temperature (MAAT) lies between 0°C and -3°C and the mean annual precipitation ranges between 150 and 500 mm, with 60-80 % of this total occurring between June through September (Leber et al., 1995). The study region features a climate gradient, with increasingly cooler and drier conditions in a westward direction.

Due to the semi-arid and cold climate conditions as well as the complex topography, soils in the study area in general are poorly developed and vegetation throughout the study area is generally sparse. The growing period lasts approximately five months, from late April/early May to late September or mid-October (Zhang et al., 2013a). The highest mountain regions are covered by glaciers and permanent snow. Among all basins, the Paiku Co catchment exhibits the largest glacier coverage (6.5 % of the basin area). The area covered by glaciers in the Nam Co, Tangra Yumco and Mapam Yumco basins accounts for 2 %, 1 % and 1.5 % of catchment area. The lake area in the several basins corresponds to 18 % (Nam Co), 11 % (Mapam Yumco), 9.5 % (Paiku Co) and 9 % (Tangra Yumco). Based on GLAS/ICESat data, the lake levels for Nam Co and Tangra Yumco rose by approximately 0.25 m yr^{-1} between 2003 and 2009; whereas, the lake levels for the Paiku Co and Mapam Yumco slightly decreased by around -0.05 m yr^{-1} (Zhang et al., 2011; Phan et al, 2012).

2.2 Data used

Because of limited availability of climatological data ~~on~~ in the TP region, we used a new atmospheric dataset for the TP, the “High Asia Refined analysis (HAR)” (Maussion et al., 2014) ~~was used~~ as input for the hydrological model. The HAR data sets were generated by a dynamical downscaling of global-analysis data (Final Analysis data from the Global Forecasting System; dataset ds083.2), using the Weather Research and Forecasting (WRF) model (Skamarock and Klemp, 2008). A detailed description of this procedure is given in Maussion et al. (2014). HAR products are freely available (http://www.klima.tu-berlin.de/HAR) in different spatial (30 km x 30 km and 10 km x 10 km) and temporal resolutions (hourly, daily, monthly and yearly). resolutions. In this study, we used the daily HAR10 data were used. In the WRF model version 3.3.1, which was used for the generation of the HAR10 data, the lake-surface temperature is initialized by averaging the surrounding land-surface temperatures. By analyzing the influence of the assimilation of satellite-derived lake-surface temperatures, Maussion (2014) found that the standard method of WRF leads to a much cooler lake than observed, which in turn has a strong influence on local climate. Therefore, the HAR10 data points over water surfaces were not included for hydrological modeling purposes.

The HAR10 precipitation output was compared to rain-gauge data and to Tropical Rainfall Measuring Mission (TRMM) satellite precipitation estimates by Maussion et al. (2014). They concluded that HAR10 accuracy in comparison to rain gauges was slightly less than TRMM; however, orographic precipitation patterns and snowfall were more realistically simulated by the WRF model. HAR10 temperatures in the summer months are closer to ground observations than in winter (Maussion, 2014). Despite the winter cold bias, the overall seasonality is well reproduced (Maussion, 2014). The cold bias effect on the accuracy of the hydrologic-modeling results is assumed to be low, because hydrological processes governing lake-level changes are more critical during the other three seasons of the year.

Lake-surface water temperature (LSWT) estimates from the ARC-Lake v2.0 data products (MacCallum and Merchant, 2012) were usedserved as additional input for the hydrological modeling in the Nam Co and Tangra Yumco basins (see Sect. 3.1.1). ARC-Lake v2.0 data products contain daytime and nighttime LSWT observations from the series of (advanced) along-track scanning radiometers for the period 1991-2011. Daytime and nighttime MODIS land-surface temperature (LST) 8-day data at 1-km spatial resolution (MOD11A2) were averaged after plausibility check to obtain mean daily LSWT time series for the Paiku Co and Mapam Yumco, where no ARC-Lake v2.0 data were available.

Shuttle Radar Topography Mission (SRTM) 90-m digital elevation model (DEM) data (Farr et al., 2007) were retrieved from the Consortium for Spatial Information (CGAIR-CSI) Geoportal (http://srtm.csi.cgiar.org). We used tThe SRTM Version 4 data were used for derivations of catchment-related information such as catchment boundary, river network, flow accumulation and flow direction, as well as terrain attributes (slope and aspect). ~~Land-cover information were derived from Landsat ETM/TM data classification (for the Nam Co and Tangra Yumco basin) or obtained from the "Himalaya Regional Land Cover" data base (http://www.glcn.org/databases/hima_landcover_en.jsp) (for the Paiku Co and Mapam Yumco basin).~~

For the Nam Co and Tangra Yumco basins, land-cover classifications were generated using Landsat TM/ETM+ satellite imagery. The land-cover classifications consist of five classes used for this analysis: water, wetland, grassland, barren land and glacier. For the Paiku Co and Mapam Yumco basin, land-cover information could be obtained from the "Himalaya Regional Land Cover" data base (http://www.glcn.org/databases/hima_landcover_en.jsp). The Himalaya land-cover map was produced as part of the 'Global Land Cover Network - Regional Harmonization Program', an initiative to compile land-cover information for the Hindu Kush-Karakorum-Himalaya mountain range using a combination of visual and automatic interpretation of recent Landsat ETM+ data. The land-cover classes were reclassified according to the five classes mentioned above. Classes with similar characteristics (e.g., vegetation type, degree of vegetation cover) were consolidated into a single class.

Lake-level observations from 2006 to 2010 for the Nam Co were provided by the Institute of Tibetan Plateau Research (ITP), Chinese Academy of Sciences (CAS) and used for model validation. However, lake-level values during the freezing (wintertime) periods are missing, because the lake-level gauge was destroyed by lake ice, and therefore, rendered inoperable each winter. Thus, data is only available for the ice-free period (May/June – November/December). Unfortunately, the lake-level observation data contain an unknown shift between the consecutive years.

Due to the absence of continuous lake-level measurements, satellite-based lake-level and water-volume data were obtained for the four studied basins from the HydroWeb data base (http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/) provided by LEGOS/OHS (Laboratoire d'Etudes en Geodesie et Oceanographie Spatiales (LEGOS) from the Oceanographie, et Hydrologie Spatiales (OHS)) (Crétaux et al., 2011). LEGOS lake-level and water-volume data for the lakes included in this study were available for different time spans (see Table 2). The start and end date of each time series were taken from the same season (as far as available) in order to make lake levels or volumes comparable. Water-volume data calculated through a combination of satellite images (e.g., MODIS, Landsat) and various altimetric height level data (e.g., Topex/Poseidon, Jason-1) (Crétaux et al., 2011) were used for model calibration (see Sect. 3.3). The mean annual lake-level changes derived from LEGOS data for the Nam Co, Tangra Yumco, Paiku Co and Mapam Yumco (0.25, 0.26, -0.07, -0.05 m yr^{-1}) ~~four basins~~ are close to the change rates estimated by Zhang et al. (2011) (0.22, 0.25, -0.04, -0.02 m yr^{-1}) and Phan et al. (2012) (0.23, 0.29, -0.12, -0.04 m yr^{-1}) using GLAS/ICESat data (2003-2009) (~~see~~ Table 4, lower part).

MODIS snow-cover 8-day data of Terra (MOD10A2) and Aqua (MYD10A2) satellites at a spatial resolution of 500 m were used for validation of the snow modeling ~~in the Nam Co basin (see Sect. 3.3)~~. As proposed in the literature (e.g., Parajka and Blöschl, 2008; Gao et al., 2010; Zhang et al., 2012), we combined Terra and Aqua data ~~were combined~~ on a pixel basis to reduce cloud-contaminated pixels. The cloud pixels in the Terra images were replaced by the corresponding Aqua pixel. For the period of time before the Aqua satellite was launched (May, 2002), this combination procedure was not possible, and we used the original MODIS/Terra snow-cover data ~~were used~~. After the combination procedure the cloud cover percentage was on average less than 1-2 % for all basins~~, with higher values during the wet summer season (~1 %) than in the drier winter season (~0.6 %)~~.

3 Methods

3.1 Hydrological model concept and implementation

The challenge for hydrological modelers is to balance the wish to adequately represent complex processes with the need to simplify models for regions with limited data availability (Wagener and Kollat, 2007). Therefore, we selected a semi-distributed conceptual model structure, primarily following the J2000g model (Krause and Hanisch, 2009)~~, was selected~~. The J2000g model is a simplified version of the fully-distributed J2000 model (Krause, 2002). ~~The J2000g model has a smaller number of calibration parameters and does not account for lateral flow processes between spatial model units.~~ The main differences with J2000 are that complex process descriptions (e.g., soil-water dynamics) are simplified leading to a reduced number of land-surface and calibration parameters in the J2000g model, and lateral flow processes between spatial model units and streamflow routing are not accounted for by the J2000g model. ~~It~~ The J2000g was successfully applied for hydrological predictions in data-scarce basins (e.g., Deus et al., 2013; Knoche et al., 2014; Rödiger et al., 2014; Pohl et al., 2015), including a previous modeling study in the Nam Co basin (Krause et al., 2010).

The conceptual model presented here was realized within the Jena Adaptable Modelling System (JAMS) framework (http://jams.uni-jena.de/). An overview of JAMS, especially the JAMS software architecture and common structure of JAMS models is given in Kralisch and Fischer (2012). Primarily, JAMS was developed as a JAVA-based framework for the implementation of model components of the J2000 model. During recent years, a solid library of single easily-manageable components has been developed by implementing a wide range of existent hydrological-process concepts as encapsulated process modules and developing new model modules, as needed. Due to the modular structure, the J2000g model could be easily adapted and extended according to the specific characteristics of endorheic lake basins in the TP region.

Meteorological data requirements ~~are~~ for this study were daily times series of precipitation, minimum, maximum and average air temperature, solar radiation, wind speed, relative humidity and cloud fraction obtained from daily HAR10 data. ~~The HAR10 data were used as climate input for the 10-year study period.~~ Daily LSWT data ~~were used~~ served as additional ~~data~~ input~~s~~ for the calculation of the long-wave radiation term over the lake surface. Process simulations were grouped into the following categories: i) lake, ii) land (non-glacierized) and iii) glacier. A schematic illustration of the model structure and a detailed description of the model components are given in the Supplement. ~~Regardless of the influence of long-term storage changes, such as deep groundwater, the net water budget of the four selected closed lake basins (in terms of lake-volume change) was estimated by summing up the runoff from non-glacierized land areas (generated by snowmelt and rainfall) and from glacier areas (generated by snow and ice melt) minus lake net evaporation (lake evaporation minus on-lake precipitation). For simplicity, the terms land runoff, glacier runoff and net evaporation are used to refer to several water-balance components. Assuming a simplified depiction of lake geometry, the modeled mean annual lake-water storage changes were divided by the corresponding lake area in order to provide mean annual lake-level change estimates for the four studied lakes.~~

~~The conceptual model presented herein was realized within the Jena Adaptable Modelling System (JAMS) framework (http://jams.uni-jena.de/). An overview of JAMS, especially the JAMS software architecture and common structure of JAMS models is given in Kralisch and~~

~~Fischer (2012). Primarily, JAMS was developed as a JAVA-based framework for the implementation of model components of the J2000 model. During recent years, a solid library of single easily manageable components has been developed by implementing a wide range of existent hydrological-process concepts as encapsulated process modules and developing new model modules, as needed. Due to the modular structure, the J2000g model could be easily adapted and extended according to the specific characteristics of closed lake basins on the TP. A schematic illustration of the model structure including several model contexts and components is presented in Fig. S1 in the Supplement.~~

In brief, we used ~~For~~ the regionalization procedure implemented in J2000g for the interpolation of the HAR10 raster points (centroid of the raster cell) to each HRU unit~~, the regionalization procedure implemented in J2000g was used~~. This combines Inverse Distance Weighting (IDW) with an optional elevation correction. ~~All data sets, except air temperature, were regionalized using only IDW.~~ Net radiation ~~and evapotranspiration were~~ was calculated following the Food and Agriculture Organization of the United Nations (FAO) proposed use of the Penman-Monteith model (Allen et al., 1998). We adapted ~~T~~the long-wave radiation part of the FAO56 calculation to the special high altitude conditions on the TP, ~~was modified~~ according to the recommendations of Yin et al. (2008), ~~. For this study,~~ and implemented the commonly used approach for calculating net long-wave radiation over water surface (e.g., Jensen, 2010) ~~was implemented in JAMS~~.

Potential evapotranspiration (PET) from land and snow surfaces (sublimation) is calculated based on Penman-Monteith (Allen et al., 1998). For the estimation of open-water evaporation rates from large lakes, we modified the Penman equation ~~modified with~~ through the addition of an empirical estimation of the lake heat storage (Jensen et al., 2005) ~~was used~~. As suggested by Valiantzas (2006), we used the reduced wind function proposed by Linacre (1993) ~~was applied~~ for the estimation of evaporation from large open-water body surfaces.

The simple degree-day snow modeling approach of the standard J2000g model version was replaced by ~~T~~the J2000 snow module that combines empirical or conceptual approaches with more physically-based routines ~~(Nepal et al., 2014) was used in this study~~. This module takes into account the phases of snow accumulation and the compaction of the snow pack caused by snowmelt or rain on the snow pack. For a detailed description see Nepal et al. (2014). ~~Glacier ice-melt rate was calculated~~ The glacier module calculates ice-melt according to an extended temperature-index approach (Hock, 1999).

Soil-water budget and runoff processes were simulated using a simple water storage approach ~~implemented in the J2000g soil module~~ (Krause and Hanisch, 2009). The storage capacity is defined from the field capacity of the specific soil type within the respective modeling unit. Actual evapotranspiration (AET) is calculated depending on the saturation of the soil-water storage, PET and a calibration parameter. The J2000g model generates runoff only when the soil-water storage is saturated. The partition into surface runoff and percolation depends on the slope and the maximum percolation rate of the respective modeling unit which can be adapted by a calibration parameter. The percolation component is transferred to the ground-water storage component. The ground-water module calculates base flow using a linear outflow routine and a recession parameter (Krause and Hanisch, 2009).

The lake module calculates the net evaporation (lake evaporation minus precipitation over the lake's surface area). The lake-water storage change is the sum of i) direct runoff and base flow from each modeling unit of the non-glacierized areas, and ii) glacier runoff (snow and ice melt, and rainfall over glaciers) from each glacier HRU minus lake net evaporation. For simplicity, the terms land runoff, glacier runoff and net evaporation are used to refer to several water-balance components. Because the J2000g model does not account for water routing and thus time delay of the discharge, the model is not fully suited to provide continuous and precise estimates of lake-water storage changes. ~~A more detailed description of the theoretical and methodological background of the model components and enhancements are given in the Supplement.~~

3.2 Delineation of spatial model entities

In order to provide spatially distributed information of landscape characteristics for the hydrological modeling, we applied the Hydrological Response Units (HRUs) approach (Flügel, 1995)~~ was applied~~. Using ArcGIS software, HRUs with similar hydrological behaviour were delineated by overlaying topographic-related and land-cover information. ~~Land-cover data were reclassified in five hydrologically relevant classes: water, wetland, grassland, barren land and glacier.~~ Soil and hydro-geology information were not included in the overlay analysis, due to a lack of detailed data. ~~In the absence of detailed spatially-distributed information of landscape parameters, as is the case for the TP, the spatial scale of model entities usually becomes coarser; whereby, the spatial homogeneity of a given HRU decreases. Nevertheless, t~~The distribution concept applied represents the landscape heterogeneity with a higher spatial resolution in the complex high mountain areas (a large number of small polygons) than in the relatively flat terrains in the lower elevations (smaller number of large polygons). The total number of HRUs varied between 1928 (Paiku Co) and 8058 (Nam Co).

3.3 Model-~~-~~parameter estimation and model evaluation

The J2000g model requires the definition of spatially-distributed land-surface parameters describing the heterogenic land surface and the estimation of~~ spatial and temporal static~~ calibration parameters. Land-surface parameters were derived from field studies or literature values. The field capacity was derived as function of the soil types obtained from own field surveys. Due to the limited availability of soil information for the TP, ~~observed ~~soil parameters were distributed according to different land-~~-~~cover and slope classes (Table 3).

Parameter~~-~~-optimization procedures are difficult to apply in data-scarce regions such as the TP (e.g., Winsemius et al., 2009). Moreover, various parameter set combinations may yield equally acceptable representation of the (often limited) calibration data, which is referred to as the equifinality problem (e.g., Beven, 2001; Beven and Freer, 2001). Due to a lack of calibration data, we used default settings or parameter values given in the literature ~~were used in this study ~~(see Table S1 in the Supplement).

Following ~~Huintjes (2014) and ~~Mölg et al. (2014), we implemented a precipitation-scaling factor ~~was implemented ~~as additional model parameter to account for i) HAR10 precipitation overestimation related to atmospheric~~-~~-model errors and/or ii) sublimation of blowing or drifting snow which was neglected in the model. ~~Mölg et al. (2014) proposed a parameter range between 0.5 and 0.8 for the precipitation-scaling factor to apply to the HAR10 data in the Zhadang glacier area in the Nam Co basin. ~~Due to the high uncertainty of the range of the precipitation-scaling factor in various regions ~~on ~~of the TP (Huintjes, 2014; Mölg et al., 2014; Pohl et al., 2015), we performed model runs with precipitation-scaling factors varying between 0.3 and 1.0 ~~(0.05 was used as factor increment)~~ with a 0.05 increment~~were performed~~. Because the precipitation-scaling factor was judged to be the parameter that contributes the most to uncertainties in model results, all other climate forcing variables and model parameters were held constant. We compared ~~S~~simulated mean annual lake-volume changes of each model run ~~were compared ~~with water-volume changes derived from remote-sensing data (Fig. 2). The dotted line in Fig. 2 indicates the lake-volume changes derived from LEGOS data (see Table 2). The model run with the minimum difference between modeled and satellite-derived lake-volume change was defined as reference run and thereby was used for an assessment of model results. The "best" match between simulated and satellite-derived lake-volume change was achieved by applying following precipitation-scaling factors: 0.80 (Nam Co), 0.75 (Tangra Yumco), 0.85 (Paiku Co) and 0.50 (Mapam Yumco). We discuss Tthe possible reasons for the lower parameter value for the Mapam Yumco basin compared to the other basins are discussed in Sect. 5.2.

Similar to the calibration process, data scarcity limited the establishment of rigorous and systematic validation tests. Because water-level measurements from Nam Co provide consistent time series between the months of June through November for the years 2006-2010, we chose this period for validation. Given the fact that water routing is not considered in the model, we compared mean monthly, instead of daily, water-level simulations and measurements. For the calculation of monthly-average lake levels, the lake-level value of the 1st of June was set to zero in each year and the subsequent values were adjusted accordingly to make the lake-level changes during the June-November period of the years 2006-2010 comparable.

For an independent assessment of the snow model capabilities, we compared modeled snow water equivalent (SWE) simulations of the Nam Co basin were compared with MODIS snow cover data (see Sect. 2.2). Because MODIS data provide no information about the amount of water stored as snow (i.e., SWE), this comparison was only possible in an indirect way by comparing the percent or fraction of snow-covered area (SCAF) derived from the model simulation and MODIS data. Any given spatial model unit was considered as snow-covered at days when the amount of SWE was larger than 1 mm a specific threshold (i.e. 1, 10, 50 mm). Then, SCAF within the Nam Co basin was calculated for each month and hydrological years (September through August). To evaluate further the plausibility of the model results, simulated glacial melt quantities in the Nam Co basin were compared with the results of SEB/MB models applied for the Zhadang glacier in the Nam Co basin, using the HAR10 data (Huintjes, 2014; Mölg et al., 2014). Further plausibility analysis of individual water-balance components have been conducted by comparing model outputs with results from other studies published in the literature (Sect. 5.1).

4 Results

Section 4.1 presents the modeling results of several hydrological components in the Nam Co basin, focusing on seasonal and year-to-year variations. The modeling results of all basins are compared in Sect. 4.2, assessing spatiotemporal variations of water-balance components and similarities and differences in the water balance from a regional perspective for the 2001-2010 period.

4.1 Seasonal and inter-annual variations of hydro-climatological components in the Nam Co basin

4.1.1 Air temperature and precipitation

The basin-average mean annual air temperature (MAAT) in the Nam Co basin was -3.5°C for the 2001-2010 period. The years in the second half of the decade were warmer compared to the first half (Fig. 3a, right panel), which is mostly related to higher winter temperatures. In terms of seasonal variation of air temperature the warmest month was July with a spatially averaged MAAT of 7°C and the coldest month was January with an average MAAT of -14°C (Fig. 3a, left panel). The monthly MAAT was below 0°C for a seven-month period (October through April) (Fig. 3a, left panel). The modeled annual precipitation varied between 270 mm (2005, 2006) and 550 mm (2008) during the 10-year period (Fig. 3a, right panel) with a mean annual value of ~400 mm. The annual precipitation totals showed a high variability compared to the 10-year annual mean. In particular, 2005 and 2006 were dry years and 2008 was an extreme wet year.

4.1.2 Snow dynamics

As simulated by the model, snow began accumulating in mid September, reaching a first smaller peak in November and the maximum peak between April and May, followed by rapid snow decay between May and June and a slower decrease until August (Fig. 4). A relatively small amount of modeled snow (between 10-15 %) was lost through sublimation during the winter compared to the amount of snow released through snowmelt during the spring and summer (Fig. 3b, left panel).

The modeled snow-covered area in the Nam Co basin was on average 25 % greater than MODIS snow cover (SCAF 28 % versus 21 %, Fig. 4). During the winter months November through April the modeled SCAF overestimated the MODIS SCAF by a factor of 2. During the months May through October, however, the modeled snow-cover extent was approximately 40 % lower compared to MODIS. Yearly values of modeled SCAF and MODIS SCAF are correlated (r = 0.86), indicating that the model captures inter-annual variability quite well.

4.1.3 Glacier melt

Glacier melt (snow and ice melt) was concentrated between June and September (Fig. 3c, left panel). The modeled glacier runoff ranged from 900 to 1700 mm yr^{-1} (Fig. 3c, right panel) with a 10-year average of ~1300 mm. Air temperature and the amount, timing, and form of precipitation were the principal controlling factors of the year-to-year variations. For example, the lower glacier melt amounts in the years 2001 and 2008 were caused by higher snow accumulation rates between May and June which led to a shortening of the ice-melt period. In contrast, lower snowfall rates at the beginning and during the ablation season in specific years (e.g., 2006) resulted in excessive ice melt, because the glacier ice was snow free for a longer time. As a consequence of higher temperatures during the last years of the study period's decade, the modeled percentage of snowfall declined, causing higher ice-melt rates in relatively wet years (e.g., 2010).

4.1.4 Evapotranspiration and runoff

About 80 % of simulated annual actual evapotranspiration (AET) occurred during the growing season (May through October) (Fig. 3d, left panel). Modeled AET had its maximum in July when the availability of soil water and energy was highest. About 70 % of annual precipitation was lost to the atmosphere by AET and did not enter the runoff. The modeled mean annual AET amounted to 290 mm, varying between 240 mm (2006) and 320 mm (2008, 2009) during the study period (Fig. 3d, right panel). The inter-annual variations of modeled AET were determined principally by precipitation (r = 0.76). Indeed, modeled AET in the year 2009 was as high as in the wettest year 2008. Analyzing the temporal variations of further climate factors controlling AET (air temperature, wind, humidity, radiation) it was noted that the year 2009 stood out due to relatively high wind speeds during this year, thus intensifying the evapotranspiration process. The simulated runoff from non-glacierized land surface varied between 50 mm in dry years (e.g., 2006) and 200 mm in wet years (e.g., 2008). The modeled year-to-year variability of runoff on non-glaciated land surfaces was strongly related to inter-annual variations of precipitation (r = 0.94).

The combination of various influencing variables such as local climate, topography, land cover, soil and hydro-geological properties leads to a spatially distributed pattern of runoff generation within the catchment. Figure 5 illustrates the variability of simulated mean annual basin-wide precipitation total and runoff from non-glacierized land surface and glacierized areas related to altitude. The area-altitude relation (hypsometry) for non-glacierized land surface and glacier areas was derived based on mean elevations of single model entities. Larger precipitation amounts in the high mountainous and hilly headwater areas resulted in higher land runoff estimates compared to lower elevation areas (Fig. 5). Indeed, the increase of the modeled mean annual land runoff rates with altitude was higher than the elevation-dependent increase of mean annual precipitation. The non-glacierized high-elevation areas characterized by sparse vegetation, poorly developed soils, steep topography and lower air temperatures indicated smaller soil water contents and lower AET rates compared to lower elevation bands, resulting in higher runoff rates. However, the modeled runoff from low-altitude glacier areas significantly exceeded the land runoff in the same elevation band, due to high ice melt rates in the ablation areas. Because of lower temperatures and higher snowfall rates at higher elevations, the modeled glacier runoff decreased with altitude.

4.1.5 Lake evaporation

The seasonal cycle of the modeled lake evaporation and the water-surface temperature is illustrated in Fig. 3e (left panel). Based on the ARC-Lake water-surface temperature, the Nam Co froze up in mid-January, or as late as early February during the 2001-2010 period. The frozen period ended between early-April and late-April. The late freeze-up dates are related to the large water volume of the Nam Co. The seasonality of the water-surface temperature with increasing temperatures in spring and decreasing temperatures in autumn is an indicator for the seasonal variation of the heat storage of the Nam Co (Haginoya et al., 2009). The released heat in autumn acts as energy source for evaporation. Thus, the modeled evaporation was higher in autumn than in spring (Fig. 3e, left panel).

The model-simulated mean annual lake evaporation for Nam Co ranged from 710 to 860 mm yr^{-1} during the last decade (Fig. 3e, right panel) with an annual mean of 770 mm. The year 2001 exhibited the lowest evaporation rate; whereas, 2009 indicated the highest evaporation amount. Inter-annual variations in modeled lake evaporation were related to specific combinations of air temperature, wind speed, radiation, water-surface temperature, and humidity in individual years (Fig. 6). The higher air temperatures toward the end of the study

~~period's decade as provided by HAR10 are mostly related to an increase in winter temperatures. This either doesn't affect lake surface water temperatures (the lake is frozen in winter), or is an artifact in HAR10. In 2001, relatively low air temperatures, wind speeds, net radiation and water-surface temperatures, and relatively high humidity related to the other years led to less evaporation. In contrast, in 2009, net radiation, wind speeds, air temperatures, and water-surface temperatures were comparatively high and humidity relatively low, enhancing the evaporation process.~~

4 Results

Section 4.1 contains the comparison of simulated and measured water levels of the lake Nam Co (Sect. 4.1.1) and of simulated snow cover dynamics with MODIS for all four study basins (Sect. 4.1.2). Section 4.2 deals with the assessment of the modeling results regarding spatiotemporal variations of water-balance components (Sect. 4.2.1) and their contributions to each basin's water balance (Sect. 4.2.2) during the 2001-2010 period.

4.1 Model evaluation

4.1.1 Comparison of simulated and measured water levels of the lake Nam Co

Lake-level observations of Nam Co indicate a distinct seasonal dynamic with continuously increasing lake levels during the months of June through September caused by runoff from the non-glacierized land surface and glacier areas, a lake-level peak in September and decreasing lake levels from October on primarily caused by lake evaporation. The overall seasonal dynamic during the June-November period is well represented by the J2000g model ($r = 0.81$) (Fig. 3). However, the model overestimates the lake level for the month of November.

In general, the magnitude of the lake level evolution is less well simulated than its timing. The comparison reveals a non-systematic pattern (Fig. 3). In 2006, the model is not able to reproduce the observed increase in lake levels. The substantial lake-level rise of Nam Co in 2008 simulated by the model compares well with observed data. However, the lake-level increase in 2009 is slightly overestimated. The absolute deviation between observed and simulated relative changes of monthly-averaged lake levels during the June-November period ranges between -0.31 m (2006) and 0.30 m (2009). The simulated relative lake-level change during the June-November period averaged over the years 2006 to 2010 is 0.41 m, which is approximately 0.05 m higher than the measured one (0.36 m).

4.1.2 Comparison of the simulated snow-cover dynamics with MODIS

The comparison of mean monthly values of modeled snow-covered area fraction (SCAF) (SWE > 1 mm) and MODIS indicates that the model captures seasonal variability quite well. However, there are large deviations in the magnitude. The modeled SCAF (SWE > 1mm) is generally greater than MODIS SCAF with higher deviations in the Mapam Yumco and Paiku Co basins (Nam Co: 30 % versus 22 %, Tangra Yumco: 17 % versus 8 %, Mapam Yumco: 54 % versus 28 %, Paiku Co: 49 % versus 20 %, Fig. 4). During the winter months November through April the overestimation by the model (up to a factor of 2) is generally higher than during the summer season. During the months May through October, the modeled SCAF (SWE > 1 mm) in the Nam Co and Tangra Yumco basins is even approximately 50 % lower compared to MODIS. Figure 4 indicates how sensitive are the results by using different thresholds for the amount of SWE to depict an area as snow-covered in the model. The use of higher thresholds (SWE > 10, 50 mm) for derivations of SCAF from the model reduces the overestimation, but also leads to an underestimation of the SCAF in early winter in most basins (Fig. 4). A threshold larger than 10 mm seems to be not appropriate in order to derive SCAF from the SWE simulations. It is more likely that the J2000g model overestimates SCAF. This will be discussed later in Sect. 5.2.

4.2 ~~Regional c~~Comparative analysis of ~~multiple~~ the four selected lake basins

4.2.1 Spatiotemporal patterns of hydrological components

The percentage of the precipitation occurring during the wet season (June through September) is more than half of the annual precipitation in all basins. Specifically, June-~~to~~through-September precipitation is approximately 80 % of the annual total in the Nam Co and Tangra Yumco basins and ~~only~~ around 60 % in the Paiku Co and Mapam Yumco basins (Fig. ~~7~~5a). This indicates a higher influence of the Westerlies in the Paiku Co and Mapam Yumco basins. ~~The seasonal dynamics of simulated snow and ice melt, land runoff, terrestrial evapotranspiration, and lake evaporation in the Tangra Yumco, Paiku Co and Mapam Yumco basins are similar to the seasonal variations described above for the Nam Co basin (Sect. 4.1).~~ As simulated by the model, snow accumulation in the basins generally occurs beginning in mid-September, reaching a first smaller peak between October and November and the maximum peak between April and May, followed by rapid decrease in snow between May and June and a slower rate of decrease until September. In the Mapam Yumco basin, simulated snowmelt starts later and occurs over a shorter time period compared to the other basins (Fig. 5b). This can be explained by lower air temperatures in this basin.

About 80 % of simulated annual terrestrial actual evapotranspiration (AET) occurs during the growing season (May-October). Modeled AET has its maximum in July when the availability of soil water and energy is highest. The seasonal cycle of modeled lake evaporation is influenced by seasonal heat-storage changes in the lakes. The released heat in autumn acts as energy source for evaporation. Thus, the evaporation is higher in autumn than in spring. Approximately 70 % of annual precipitation is released to the atmosphere through AET and does not contribute to the runoff in all basins. Discharge from non-glacierized land areas is concentrated during the wet season (~80 % of annual runoff occurs during May through October). Runoff starts to increase in spring with the beginning of snowmelt. The land runoff peak in the Mapam Yumco basin occurs one month earlier (between June and July) compared to the other basins (Fig. 5c), because of a higher contribution of snowmelt to the discharge. Glacier runoff occurs during June through September in all basins (Fig. 5d), but with a later beginning and a shorter duration of the melt season in the Mapam Yumco basin due to the colder climate conditions.

Table 4 (upper part) summarizes annual means of modeled water-balance components for the 2001-2010 period for each basin. The annual mean of the model-simulated lake evaporation rates varied varies between 700 and 900 mm yr^{-1} in for the four basins for the study period. In all four basins, the modeled on-lake precipitation was three to four times lower than the water loss by lake evaporation. Because of unlimited water availability, the modeled mean annual lake evaporation was is substantially approximately three to four times higher than the land AET (see Table 4, upper part).

Due to higher precipitation amounts in the eastern part of the study region, the simulated mean annual AET was is higher in the east (~290 mm in the Nam Co basin) than in the west (~170 mm in the Mapam Yumco basin) (Table 4, upper part).

According to Impacted by the decreasing precipitation gradient spatially from east to west, the model-simulated mean annual land runoff in the Nam Co basin (~130 mm) was is estimated to be more than twice that also around twice as high as in the Mapam Yumco basin (~60 mm) during the study period (Table 4, upper part). ~~The percentage of the annual precipitation which was lost by terrestrial AET increases with decreasing precipitation totals from 69 % (Nam Co basin) to 74 % (Mapam Yumco basin) (Table 4). Within all the catchments, the AET/precipitation ratio decreases with altitude as described for the Nam Co basin (Section 4.1.4).~~ The combination of various influencing variables such as local climate, topography, land cover, soil and hydro-geological properties results in a spatially heterogeneous pattern of runoff generation within the catchments. Figure 6 illustrates the altitudinal dependence of the mean annual basin-wide precipitation total and runoff from non-glacierized land surface and glacierized areas, as computed by the J2000g model. The area-altitude relation (hypsometry) for non-glacierized land surface and glacier areas is based on mean elevations of the respective model entities. Larger precipitation amounts in the high mountainous and hilly headwater areas result in higher land runoff estimates compared to lower elevation areas (Fig. 6). Indeed, the increase of land runoff with altitude is higher than the elevation-dependent increase of precipitation. The non-glacierized high-elevation areas characterized by sparse vegetation, poorly developed soils, steep topography and lower air temperatures indicate smaller soil-water contents and lower AET rates compared to lower elevation bands, resulting in higher runoff rates.

In all studied basins, the runoff from glacier areas located in lower elevations zones (<5750 m a.s.l.) significantly exceeds the land runoff in the same elevation zones (Fig. 6), due to high ice-melt rates in the ablation areas. Because of lower temperatures and higher snowfall rates at higher elevations, the modeled glacier runoff decreases with altitude.

~~On average, t~~ The modeled mean annual glacier runoff ~~rates~~ averaged over all glacier HRUs in the Nam Co and Tangra Yumco basins (~1300 mm) ~~were~~ is ~~approximately two to four times~~considerably higher than in the Paiku Co (~300 mm) and Mapam Yumco (~600 mm) basins~~,~~. ~~which was~~ This is judged to be caused ~~principally~~ by lower air temperatures (~2°C less) in the glacier~~ized~~ areas of the Paiku Co and Mapam Yumco basins.

~~4.2.2 Regional differences in the water balance~~

4.2.2 Contributions of the individual hydrological components to the water balance

~~The water volume of the four lakes included in this study generally increases during the months of June through September. This is due to the following factors: i) runoff from the~~

~~non-glacierized land surface generated by snowmelt and direct rainfall, and ii) water from glacial melting. Then the lake's water-volume decreases until May of the following year, primarily as a result of lake evaporation or sublimation. The relation between water loss through net evaporation and water gain through runoff from non-glacierized and glacier areas in essence sets each basin's water balance. ~~Table 4 (lower part) summarizes m~~M~~odel-simulated mean annual lake-volume and level changes and the contribution of non-glacierized land, glacier, and lake areas to the total water-budget during the 2001-2010 study period~~ for the four basins are summarized in Table 4~~. Comparative values for the mean annual lake-level changes derived from remote-sensing data also are given in Table 4 (lower part).

~~The total water inflow in the Tangra Yumco and Nam Co basins exceeded the water loss by a factor of 1.4 or 1.5, respectively. Because of the small portion of glacier areas (1-2 % of the total basin area, Table 1), the mean annual contribution of modeled glacier-melt water to total basin runoff volume was only 14 % in the Tangra Yumco and 19 % in the Nam Co basin. In contrast to Nam Co and Tangra Yumco, the water loss term for Paiku Co exceeded the water gain terms by 10 %; whereas, in the Mapam Yumco basin the water gain and loss terms tended to balance each other out. The glacierization in the Paiku Co basin is about three to six times larger than in the other three basins, but the glacier melt contribution to the total basin runoff volume was only 30 % during the study period. The differences in the water balance among the four basins over the study period were primarily caused by relatively lower land runoff contributions in the Paiku Co and Mapam Yumco basins compared to the Nam Co and Tangra Yumco basins. This is related to lower precipitation totals in the Paiku Co and Mapam Yumco basins compared to the other two basins.~~The contribution of glacier runoff to the total basin runoff volume in the Nam Co (19 %), Tangra Yumco (14 %) and Mapam Yumco (15 %) basins is relatively low compared to the runoff contribution from non-glacierized land areas. The glacierization in the Paiku Co basin is about two to five times larger than in the other three basins, but the glacier-melt contribution to the total basin runoff volume is only around twice as high (30 %) due to lower glacier-melt rates. Despite the generally higher glacier contribution in the Paiku Co, the water balance is slightly negative during the study period (Table 4, lower part). The water loss for Paiku Co exceeds the water gain by 10 %. In contrast, the total water inflow in the Tangra Yumco and Nam Co basins exceeds the water loss by a factor of 1.4 or 1.5, respectively. In the Mapam Yumco basin the water gain and loss terms tend to balance each other out (Table 4, lower part), based upon the model simulation.

In order to better predict and understand the role of glaciers for the mean annual water balance, a hypothetical scenario with ice-free conditions were evaluated through model simulations for each lake basin. Therefore, the land-cover class of all glacier HRUs was changed to barren land. In the absence of glaciers, the total runoff volumes in the Nam Co and Tangra Yumco basins would be about 13 % lower than with ice-melt water contribution during the 2001-2010 period (compared to the reference run). Thus, the mean annual lake-level increases of Nam Co and Tangra Yumco would be reduced from 0.24 to 0.15 m and from 0.29 to 0.17 m, respectively. In the Mapam Yumco and Paiku Co basins, the total runoff volumes would decrease by approximately 30 % and the resulting mean annual lake-level changes would change from 0.02 to -0.18 m and from -0.07 to -0.25 m, respectively, under ice-free conditions. From this latter evaluation, it can be concluded that the mean annual net water budget would noticeably change without ice-melt water contribution; however, the water balance in the Nam Co and Tangra Yumco remains positive.

Based upon the J2000g modeling results, the differences in the water balance among the four studied lakes are primarily caused by relatively higher land runoff contributions in the Nam Co and Tangra Yumco basins compared to the Paiku Co and Mapam Yumco basins. This is related to relatively higher precipitation totals in the Nam Co and Tangra Yumco basins compared to the other two basins during the 2001-2010 period.

Figure ~~8a~~7a-d (upper panels) illustrates the yearly water contribution in km³ of each land cover type (land, glacier, and lake) for the 2001-2010 period. The annual percentage deviations from the 10-year average of several hydrological system components are presented in Fig. ~~8a~~7a-d (lower panels). ~~The modeled annual lake-volume changes of all studies lakes are highly correlated to inter-annual variations of land runoff (r ≈ 0.99). No correlation was found between annual glacier melt amounts and lake-volume changes in the four basins.~~

Over the study period, annual relative lake-volume changes in the four basins indicate~~d~~ similar patterns. A relatively high correlation of lake-volume changes ~~was~~ is found between the Nam Co and Tangra Yumco basin (r = 0.82)~~, which~~. These are the basins with a higher proportion of June-through~~o~~-September precipitation compared to the Paiku Co and Mapam Yumco basins.

The modeled annual lake-volume changes of all ~~studies~~ four lakes are highly correlated to inter-annual variations of land runoff (r ≈ 0.99). The year-to-year variability of runoff from non-glacierized land surfaces, in turn, is strongly related to inter-annual variations of precipitation (r ≈ 0.92). Inter-annual variability of lake evaporation is low in all four studied basins and not correlated to lake-level changes. Thus, lake evaporation seems to have a minor impact on inter-annual lake-level variations during the study period. There is also Nno correlation was found between annual glacier melt amounts and lake-volume changes infor the four basins. This suggests that glacier-melt runoff is not the main driving force for inter-annual lake variations during the last decade. Although the modeled annual glacier runoff was is above greater than the 10-year average in the year 2006 in all basins, lower precipitation amounts lead to less land runoff, causing a lake-volume decrease in this year in all basins. In contrast, the year 2008 might be considered is judged as having anomalous conditions, with modeled precipitation and land runoff substantially above average and with below-average glacier melt, resulting in a lake-volume increase in all basins. Differences in annual lake-volume changes among the basins are caused principally by regional differences in the inter-annual variations of precipitation. To explore the mechanism controlling spatial patterns of precipitation in single years was beyond the scope of this study.

5 Discussion

5.1 Comparison with other studies

5.1.1 Estimation of the water-balance components

Due to the scarcity of field measurements in the TP region, the research on spatiotemporal variations of water-balance components and on their environmental controls is limited model simulations of water-balance components are limited in the TP region. Evaporation over lake surfaces has been estimated for only few lakes on the TP, based on model simulations (e.g., Morrill, 2004; Haginoya et al., 2009; Xu et al., 2009; Yu et al., 2011). Mean annual lake-evaporation estimates on the TP vary between 700 and 1200 mm. Our results The lake-evaporation rates simulated with the J2000g model (between 710 and 910 mm yr^{-1}) are within this range (Table 4). There are only few studies for the TP for assessing the actual evapotranspiration over alpine grassland, based on measurements and model simulationsestimations (e.g., Gu et al., 2008; Yin et al., 2013; Zhu et al., 2014). Yin et al. (2013) estimated AET over the entire TP using meteorological data available between 1981 and 2010 from 80 weather stations as model input for the Lund-Potsdam-Jena dynamic vegetation model (Sitch et al., 2003). For the south-central TP, the simulated mean annual

AET ~~ranged~~ ranges from 100 to 300 mm, with generally higher values in the east and lower values in the drier regions in the west. Our ~~model~~-simulated AET estimates for the four basins ~~varied~~ vary between 170 and 290 mm yr^{-1}, decreasing from east (Nam Co basin) to west (Mapam Yumco basin) (Table 4). This compares favorably with the study ~~of~~ reported by Yin et al. (2013).

Using a simplified procedure, Yin et al. (2013) developed spatial patterns of the surface-water budget over the entire TP for the 1981-2010 period by estimating the difference between precipitation and AET (P-AET). The results revealed that P-AET depends on climate regimes and gradually decreases from the east (~150 mm yr^{-1}) to the west (~50 mm yr^{-1}) in the study region. Our model simulations indicate quite similar runoff patterns compared to the findings of Yin et al. (2013), with decreasing annual means from the east (~130 mm in the Nam Co basin) to the west (~60 mm in the Mapam Yumco basin). The calculated AET/precipitation ratio of around 0.7 in all basins agrees well with study results from Gu et al. (2008).

~~In order to evaluate the plausibility of glacier-runoff simulations, the modeled glacial-melt quantities in the Nam Co basin were compared with the results of SEB/MB models applied for the Zhadang glacier in the Nam Co basin, using the HAR10 data (Huintjes, 2014; Mölg et al., 2014). The comparison revealed that the modeled basin-wide mean annual glacier runoff of ~1300 mm is in the same order of magnitude as simulated by the SEB/MB models for the Zhadang glacier. The modeled year-to-year variability with lower melt rates in the years 2001-2004 and 2008, and higher melt rates in the years 2005-2007, 2009 and 2010 agreed well with the findings of Mölg et al. (2014). Nevertheless, the range between individual years was more pronounced using the energy-balance approach.~~ The mean annual glacier runoff of 1320 mm, simulated with the J2000g model for the Nam Co basin, compares quite well with estimated glacier-melt quantities for the Zhadang glacier in the Nam Co basin using more complex SEB/MB models (Mölg et al., 2014: 1375 mm yr^{-1}; Huintjes et al., 2015: 1325 mm yr^{-1}).

5.1.2 Factors controlling the water balance and lake-level variability

Many studies emphasize the importance of glacier-meltwater contribution to the water budget of Tibetan lakes (e.g., Zhu et al., 2010). However, only few studies have quantitatively estimated glacier-meltwater contribution to total runoff in the TP region, due to the difficulty to estimate glacier-volume changes (Li, B. et al., 2014). ~~Regarding the low contribution of glacier melt water to total runoff, it was also found by Li et al. (2014a) that glacier runoff~~

~~plays a minor role compared to snowmelt and rainfall runoff components from non-glacierized areas. For the period 2006-2011, they~~ Li, B. et al. (2014) estimated a glacier runoff contribution of 15 % ~~to~~ of the total runoff (during 2006-2011) in a sub--basin of the Nam Co basin, the Qugaqie basin (8.4 % glacierized coverage area), using an energy-balance based glacier-melt model and the "Gridded Subsurface Hydrologic Analysis (GSSHA) model" (Downer and Ogden, 2004). Based upon the J2000g model results, the glacier contribution ranges between 14 and 30 % in the four studied basins (1-6 % glacier coverage) during the 2001-2010 period. This range of value is slightly higher than that computed by Li, B. et al. (2014) considering the percentage of basin area covered by glaciers.

Simulated glacier-meltwater contribution is generally lower compared to the runoff contribution from non-glacierized areas; however, glaciers make an important contribution to the water budget during the 10-year period considering the small extent of ice-covered areas in the four studied lake basins. Indeed, the water balance in the Nam Co and Tangra Yumco basins would also be positive without ice-meltwater contribution during the study period, based on the results of the ice-free scenarios. Thus, the question arises why the Nam Co and Tangra Yumco indicate a non-equilibrium state; whereas, Paiku Co and Mapam Yumco are at a state close to the hydrologic equilibrium.

Endorheic lakes respond to climatic changes to maintain equilibrium between input and output, and to reach steady state. Due to the time lag of lakes in responding to climatic changes, this modeling study cannot confirm whether or not the shift towards a positive water balance in the Nam Co and Tangra Yumco basins or the negative shift in the water balance of the Paiku Co basin, respectively, was primarily caused by changes in precipitation, glacier melt, evapotranspiration, etc. However, inter-annual lake-level variations are highly positively correlated with precipitation and land runoff. This supports the assumption of other studies (e.g., Lei et al., 2014; Li, Y. et al., 2014; Song et al., 2014) that increasing precipitation is the primary factor causing lake-level increases in the central TP (where Nam Co and Tangra Yumco are located). The relative stability or slight lake-level declines in the marginal region of the TP (where Paiku Co and Mapam Yumco are located) seem to be related to relative stable or slightly decreased precipitation (e.g., Lei et al., 2014). Both changes in large-scale circulation systems and local circulation are assumed to be responsible for spatially varying changes in moisture flux over the TP (e.g., Gao et al., 2014, 2015). However, these factors are still under debate and further research is needed (Gao et al., 2015).

A decreasing trend in potential evaporation before 2000 might have resulted in rising lake levels in the central TP. However, this factor did not prevent the lake shrinkage along the south-west periphery of the TP, indicating that lake evaporation is not a primary factor for explaining the spatial differences of lake-level changes between the central and southern TP (Lei et al., 2014). In addition, Li, Y. et al. (2014) argued that recent rapid lake expansion in the central TP cannot be explained by changes in potential evaporation, because the overall increasing tendency of potential evaporation in the TP region after 2000 (Yin et al., 2013; Li, Y. et al., 2014) would negate the effect of increasing precipitation on lake levels.

Under the assumption that glacier-melt runoff increased during the last decades due to climate warming, it is very likely that glacier-meltwater supply augmented the precipitation-driven lake areal expansion in the central TP region (Song et al., 2014). In the Mapam Yumco and Paiku Co basins, glacier-meltwater discharge might have mitigated lake-level declining and acted as a regulating factor (Ye et al., 2008; Nie et al., 2012).

Li, Y. et al. (2014) suggest that spatial variations in lake-level changes might be related to different distributions and types of permafrost. Most lakes in the central-northern TP with continuous permafrost are rapidly expanding; whereas, lakes in the southern region with isolated permafrost are relatively stable or slightly decreasing. Thus, accelerated permafrost melting might have contributed to the rapid lake expansion in the central and northern TP subregions (Li, Y. et al., 2014). The water contribution from permafrost will become limited when ground temperature increases above the melting point of the frozen soil (Li, Y. et al., 2014). Li, Y. et al. (2014) suggest that permafrost-meltwater contribution may have become already limited in the southern TP. However, this is difficult to corroborate given the absence of observational data for the studied lake basins. The questions remain i) how large is the volume of water released due to thinning and thawing of permafrost, and ii) to what extent can it modulate basin runoff. These cannot be answered without adequate information about permafrost occurrence, thickness and ice content in the studied basins.

Differences in the response time or, in other words, the time required to reach an equilibrium state could also be a reason for observed differences in lake-level changes. Based upon remote sensing data, the lake areas of Nam Co and Tangra Yumco expanded by 4.6 and 1.8 %, respectively, between 1970 and 2008 (Liao et al., 2013). The lakeshore slopes of Tangra Yumco are steeper compared to the Nam Co. Steep-sided lakes have a longer equilibrium response time, because of a lower rate of change of the lake area with volume (Mason, 1994).

Based upon paleo-shorelines, the post-glacial lake-level high of the Nam Co and Tangra Yumco was about 29 m (Schütt et al., 2008) and 185 m (Rades et al., 2013), respectively, above the present-day lake level, supporting the assumption that the Nam Co has a shorter response time to compensate for the increment in net inflow (i.e. faster and stronger reaction of its lake area). Moreover, the water supply coefficient (basin area/lake area ratio) for the Nam Co is smaller than for the Tangra Yumco basin (5.5 versus 11.0).

The lake extent of Paiku Co and Mapam Yumco decreased by 3.7 and 0.8 %, respectively, between 1970 and 2008 (Liao et al., 2013). The lakeshores of Mapam Yumco are generally flatter compared to the Paiku Co. However, due to only small lake-area variations of Mapam Yumco during the last decades (Liao et al., 2013), differences in lake morphology seem not to be the reason for the relative stability of the recent water levels of Mapam Yumco. Differences in the water-supply coefficient of the Paiku Co and Mapam Yumco basin are quite low (8.8 versus 10.6).

Based upon results of other studies in the region (e.g., Lei et al., 2013), the effects of upwelling and downwelling groundwater related to fault zones and lake-groundwater exchanges on the water balance were assumed to be negligible. However, Zhou et al. (2013) suggest that water leakage related to seepage might play an essential role in the hydrological cycle of the TP due to the large numbers of lakes and the sub-surface fault system in the TP region. Groundwater outflow from the Mapam Yumco to the Langa Co (located only a few kilometers to the west about 15 m below the Mapam Yumco) cannot be excluded and could be a reason for the relatively stable water levels of Mapam Yumco. In the more recent past, the Mapam Yumco and the Langa Co were connected by the natural river Ganga Chu having an extent about 10 km. However, currently there is no surface outflow (Liao et al., 2013).

5.2 Limitations and uncertainties

~~Hydrological modeling studies in ungauged or poorly gauged basins are generally fraught with uncertainty most related to the fact that reliable input data are not available and process dynamics are often unknown and/or unobservable.~~ Hydrological ~~predictions~~ modeling ~~in data-scarce regions are~~ ~~severely~~ is hindered by systematic or random model-input errors, model-parameter uncertainty and model-structure inadequacies (Sivapalan, 2003). ~~Model-input uncertainty stems from the fact that HAR10 grid points surrounding the lakes were used as input for the modeling of lake evaporation and estimation of on-lake precipitation.~~ As stated in many studies (e.g., Knoche et al., 2014; Pohl et al., 2015), precipitation input is the primary source of uncertainty ~~for~~ in hydrological modeling studies in data-scarce regions. ~~The HAR10 precipitation output was compared to rain gauge data and to TRMM satellite precipitation estimates by Maussion et al. (2014). They concluded that HAR10 accuracy in comparison to rain gauges was slightly less than TRMM; however, orographic precipitation patterns and snowfall were more realistically simulated by the WRF model. The comparison of HAR10 precipitation with observations primarily located near population centers in lower elevations in the eastern part of the Plateau revealed a non-systematic error pattern (Maussion et al., 2014). In particular, precipitation totals in the summer of years 2007-2010 indicate a positive bias (Maussion et al., 2014). The reasons for these discrepancies for some years are unclear. The differences after 2007 may be associated with changes in the global data assimilation system (Maussion et al., 2014). However, the uncertainty of HAR10 precipitation in complex terrain such as in the case study basins, where no measurements are available, is unknown. Following Huintjes (2014) and Mölg et al. (2014), a precipitation-scaling factor was applied in all basins. The precipitation-scaling factors were kept constant for the entire 10-year period. Indeed, this may have had an impact on inter-annual variations of modeling results if there is a non-systematic error pattern in the HAR10 precipitation data.~~ HAR10 data has been successfully used as modeling input in various studies (Huintjes, 2014, Mölg et al., 2014; Huintjes et al., 2015; Pohl et al., 2015). However, these studies also needed to apply a precipitation-scaling factor < 1. Maussion et al. (2014) could not find a systematic bias in comparison with station observations, but it is probable that overestimation of precipitation amounts occurs at high altitudes.

The precipitation-scaling factors were kept constant for the entire 10-year period, because there is no opportunity to derive varying scaling factors for individual years, due to a lack of observations in the lake basins included in this study. This may have an impact on inter-annual variations of modeling results. The non-systematic deviations between simulated and measured lake levels of the Nam Co (Fig. 3) might be related to a non-systematic error pattern in the HAR10 precipitation data. The primary issue is that HAR10 precipitation cannot be validated to a sufficient degree, because available data are for stations that are located at lower elevations, and no accuracy assessment can be done for the higher elevation zones where study basins are located. The comparison with available station data suggests that the accuracy of the precipitation data is probably regionally dependent (Maussion et al., 2014).

This makes it difficult to find a fixed precipitation-scaling factor that is applicable for different regions of the TP.

As described in Sect. 3.3, we conducted multiple model runs using precipitation-scaling factors between 0.3 and 1.0, seeking a precipitation-scaling factor that best simulates satellite-derived lake-volume changes. There may be errors in the satellite-derived water-volume data, which in turn might have affected the estimation of the precipitation-scaling factor and thereby the accuracy of model results. However, the precipitation-scaling factors obtained for the Nam Co (0.80), Tangra Yumco (0.75) and Paiku Co (0.85) basins are relatively close to the scaling factor used for the Zhadang glacier in the Nam Co basin in the study of Mölg et al. (2014). They found very good agreement between glacier mass-balance model calculations and available in-situ measurements by applying a precipitation-scaling factor of 0.79. This gives us confidence that the scaling factors used in our study seemed to be within an acceptable range.

The relatively low precipitation-scaling factor of 0.50 obtained for the Mapam Yumco basin seems to be plausible when comparing HAR10 precipitation with weather station data of Burang (30°17'N, 81°15'E, ~30 km to the south, closest station with available data) published in Liao et al. (2013). The mean annual precipitation total of Burang is 150 mm yr^{-1} for the period 2001-2009; whereas, the nearest HAR10 point gives a mean annual precipitation amount of 330 mm yr^{-1}. Huintjes (2014) also found that a reduction of the precipitation by more than 50 % leads to more reliable mass-balance results for the Naimona'nyi glacier (Gurla Mandhata, south western TP) which is located close to the Mapam Yumco basin.

Uncertainty arises also from the fact that the precipitation-scaling factor can compensate for not only input data errors but also model-structure inadequacies~~,~~. Blowing-snow sublimation was neglected in our modeling approach, due to the complexity of this process in complex terrain (Vionnet et al. 2014).~~ in particular~~ However, wind-induced sublimation of suspended snow above the snow pack ~~which~~ can be a significant water loss to the atmosphere (e.g., Bowling et al., 2004; Strasser et al., 2008; Vionnet et al., 2014). Vionnet et al. (2014) simulated total sublimation (surface + blowing snow) in alpine terrain (French Alps) using a fully coupled snowpack/atmosphere model. They estimated that blowing-snow sublimation is two thirds of total sublimation. ~~Blowing-snow sublimation was neglected in our modeling approach, due to the complexity of this process in complex terrain (Vionnet et al. 2014).~~

However, tThis process is judged to be important in the study area, due to the relatively dry near-surface conditions and relatively higher wind speeds occurring during the winter months. Thus, the low values of scaling factor applied in the Mapam Yumco basin (0.5) and in the study of Pohl et al. (2015) (0.37) might be an indication that drifting-snow sublimation plays a greater role in regions which are stronger influenced by Westerlies.

The omission of processes such as snow redistribution by wind and avalanches and snow loss by blowing-snow sublimation may affect snow-cover patterns as well as the magnitude and timing of melt runoff (Pellicciotti et al., 2014). This could also be a reason for the larger areal snow-cover extent in the model simulation during the winter season compared to MODIS (Section 4.1.2). Explanations for the lower SCAF values of the model during the summer period could be related to the fact that the MODIS/Terra data are collected only in the morning (10:30 AM) rather than at several times during the day. That means that MODIS indicates snow cover at days when snow was accumulated during the previous night or early morning but which might be sublimated or melted later during the day (Kropacek et al., 2010).

As described in Sect. 3.3, multiple model runs were conducted using precipitation-scaling factors between 0.3 and 1, seeking a precipitation-scaling factor that best simulates satellite-derived lake-volume changes. Figure 2 indicates how sensitive the model results are to the precipitation-scaling factor. The lower precipitation-scaling factor of 0.50 for the Mapam Yumco basin compared to the other three basins, where scaling factors between 0.75 and 0.85 resulted in the “best” match between simulated and satellite-based water-volume changes, might be an indication either that HAR10 precipitation is significantly overestimated in this specific basin or that drifting snow sublimation plays a greater role than in the other basins. Huintjes (2014) also found that the use of a precipitation-scaling factor lower than the factor applied to the Zhadang glacier in the Nam Co basin lead to more reliable glacier mass balance results for the Naimona’nyi glacier (Gurla Mandhata, south western TP) which is located close to the Mapam Yumco basin. A further source of uncertainty is that there may be errors in the satellite-derived water-volume data, which were used for the setting of the precipitation-scaling factor. Thus, errors in satellite-based lake-volume changes might have affected the setting of the precipitation-scaling factor and thereby the accuracy of model results. Apart from the precipitation-scaling factor, default settings of the J2000g model were applied or parameter values were taken from the literature due to missing calibration data.

Therefore, model outputs might also be influenced by assumptions on certain key model parameters other than the precipitation-scaling factor.

In respect to the gGiven the limited data availability, further assumptions about orand simplifications of the systemin the model were required. The currently implemented glacier-melt model component according to Hock (1999) is a simple, robust and easy to use methodology that does not account for the transformation of snow into ice. Thus, simulated snowmelt amounts on glacier surfaces might be overestimated. Because glacier-volume changes are not considered in J2000g, unrealistic amounts of glacier-meltwater could be generated. However, the impact of this effect on model results is assumed to be small over the 10-year period. The consideration of glacier-volume changes would be of higher importance for long-term model simulations. The less complex model structure might be a major factor for a lower year-to-year variability compared to the SEB/MB model results (Huintjes, 2014; Mölg et al. 2014). Furthermore,

eEffects of lake-groundwater interactions were neglected in the model applications to basins in the TP region, because the quantification of flow between aquifer systems and a deep lake is difficult (Rosenberry et al., 2014). However, it is unclear if and to what extent intermittent (at irregular time intervals) exfiltration (flow from groundwater to a lake) and infiltration (flow from a lake to groundwater) processes might occur, thereby impacting water-level changesfluctuations. The stated values of lake-groundwater exchange rates do strongly vary within literature by more than five orders of magnitude (Rosenberry et al., 2014). The relative contribution of exfiltration to input terms in lake-water budgets ranges from near 0 % to 94 %, and infiltration contribution to loss terms ranges from near 0 % to 91 % (Rosenberry et al., 2014). The lack of consideration of lake-groundwater interactions could be the reason that the observed lake-level decrease of the Nam Co during the months of October and November is not well represented by the model. If lake levels rise higher than adjacent ground-water levels, lake water may move into the adjacent lakeshores' subsurface. This additional storage factor would basically have a dampening effect on lake-level dynamics. However, in view of multi-annual lake changes, lake-groundwater exchanges are assumed to be negligible.

5.3 Factors influencing long-term lake-level changes

Under constant climatic conditions, closed lakes should eventually tend to attain a stable equilibrium, where several water-balance terms tend to balance each other out. Although the

Paiku Co and Mapam Yumco were at a state near to the hydrologic equilibrium during the study period, the Nam Co and Tangra Yumco with a lake level increase between 0.2 and 0.3 m yr^{-1} indicate a non-equilibrium state. During recent decades, the central and eastern part of the TP exhibited an increasing trend in precipitation (Yin et al., 2013) which might be a primary reason for the positive water balances noted for the Nam Co and Tangra Yumco during the last decade. For a closed lake, where the lake evaporation is higher than the on-lake precipitation, the lake area and thus lake evaporation will increase over time as consequence of a positive water balance. Thus, this has the consequence that the lake volume rate of change will be reduced over time. The time lag in the response of the area of a closed lake to climate fluctuations or, in other words, the time required to reach an equilibrium depends upon the climate over each lake and associated catchment area and the geomorphological characteristics of the lake. The more arid the climate conditions and the higher the rate of change of a given lake's area with volume, the faster the lake can adjust its area (and thus its net evaporation rate) to compensate for a given increment in net inflow (Mason, 1994). Thus, different lake response times need to be considered when analyzing long-term water-balance changes.

6 Conclusions and outlook

Lake-level changes as an indicator for differences in water-balance changes on the TP have become a focal point for research in recent years. This research highlights the possible benefit for conducting quantitative hydrological-modeling studies to explore the causes of lake-level changes. In this study, the hydrological model J2000g was extended and applied to endorheic lake basins on the TP aiming to provide a more quantitative understanding of the key factors controlling the water-balance on the TP. The model results indicated that the relative contribution of glacier runoff to total water inflow (between 15-30 %) plays a relatively minor role, compared to precipitation and snowmelt runoff components from non-glacierized areas. Indeed, the glacier derived runoff contribution increases during dry years. The small glacier contribution to the basin water balance is related to the low percentages of glaciers in the selected basins (ranging between 1-7 %) during the study's period (2001-2010). It is concluded that the positive water balance in the Nam Co and Tangra Yumco basins was caused by higher precipitation totals and thus higher land runoff rates compared to the Mapam

Yumco and Paiku Co basins with relative stable or slight negative water balances, respectively.

Hydrological modeling is required to allow for a quantitative assessment of differences in the water balance and thus a better understanding of factors affecting water balance in the TP region. Addressing this research need, we developed a modeling framework integrating atmospheric-model output and satellite-based data, and applied it to four selected endorheic lakes across the southern-central part of the TP. The hydrological model J2000g was adapted to the specific characteristics of endorheic lake basins in the TP region. The model-derived atmospheric data HAR10 and satellite-derived lake-water surface temperature served as input for the modeling period 2001-2010. Due to missing continuous lake-level in-situ data, we used satellite-derived lake-volume changes as a model performance criterion.

The adapted J2000g model version reasonably captured seasonal dynamics of relevant hydrological processes. Water-balance estimates of individual years should be considered carefully, due to possible unsystematic error patterns in HAR10 precipitation. Nevertheless, uncertainties which appear to be related to the precipitation-scaling factor, should not affect the overall conclusions drawn from the model results.

The major outcomes can be summarized as follows:

- The seasonal hydrological dynamics and spatial variations of runoff generation within the basins are similar for all studied lake basins; however, the several water-balance components vary quantitatively among the four basins.
- Differences in the mean annual water balances among the four basins are primarily related to higher precipitation totals and attributed runoff generation in the basins with a higher monsoon influence (Nam Co and Tangra Yumco).
- The glacier-meltwater contribution to the total basin runoff volume (between 14 and 30 % averaged over the 10-year period) plays a less important role compared to runoff generation from rainfall and snowmelt on non-glacierized land areas. However, considering the small part of glacier areas in the study basins (1-6 %), glaciers make an important contribution to the water balance.
- Based upon hypothetical ice-free scenarios in the hydrological model, ice-melt water constitutes an important water-supply component for basins with lower precipitation (Mapam Yumco and Paiku Co), in order to maintain a state close to equilibrium;

whereas, the water balance in the basins with higher precipitation (Nam Co and Tangra Yumco) would be still positive under ice-free conditions.

- Precipitation and associated runoff are the main driving forces for inter-annual lake-level variations during the 2001-2010 period. Both are highly positively correlated with annual lake-level changes, whereas no correlation is found between inter-annual variability of lake levels and glacier runoff or lake evaporation.

For the 10-year modeling period used in this study, it is not possible to draw definitive conclusions regarding the hydrological changes that might have led to imbalances in the water budgets of the four studied lakes. However, the model results support the assumption of other studies that contrasting patterns in lake-level fluctuations across the TP are closely linked to spatial differences in precipitation.

This study demonstrates the feasibility of a methodological approach combining distributed hydrological modeling with atmospheric-model output and various satellite-based data to overcome the data-scarcity problem in the TP region. The integration of readily available model-derived atmospheric and remote-sensing data with hydrological modeling has the potential to improve our understanding of spatiotemporal hydrological patterns and to quantify water-balance components, even in ungauged or poorly gauged basins. The modeling framework presented in this study provides a useful basis for future regionally focused investigations on the space-time transition of lake changes in the TP region.

~~Data scarcity on the TP complicates model parameter setting and limits the implementation of rigorous and systematic validation testing. Therefore, m~~ Model applications in such a data-scarce region have inherent uncertainty which should be perceived as useful information rather than a lack of basic knowledge or understanding (Blöschl and Montanari, 2010). An uncertainty and sensitivity analysis that includes the assessment of spatially and temporally variable effects on model outputs will allow specific and detailed recommendations on the timing and locations of future field measurements (e.g., Ragettli et al., 2013).

~~In general, t~~There is an urgent need in such studies for meteorological observations (particularly precipitation in high mountain regions) and monitoring of land-surface characteristics (vegetation, soil and hydrogeological properties), in order to reduce the model uncertainties arising from input data and land-surface parameterization. ~~Moreover, observations of blowing-snow sublimation and lake-groundwater exchanges would be very helpful to clarify their role in the water balance.~~

Overall, future research should focus on model-independent data describing hydrological system components which can be used for multi-response calibration and validation purposes. Water-level and volume estimations with a higher temporal resolution are expected to be produced from new satellite-altimetry data, such as from Cryosat (continuously data available since 2012, planed until 2017), Sentinel-3 (2015) and Jason-CS (2017) (Kleinherenbrink et al., 2015), which could be used as calibration or validation data in further model applications in the future. ~~Moreover, atmospheric data at higher than 10 km x 10 km resolution would allow more reliable estimations of hydrological components in future modeling studies.~~

Author contribution

S.B. designed the study, extended the J2000g model, performed modeling studies, analyzed data and wrote the main paper and the supplementary information. F.M. developed HAR and analyzed HAR data. P.K. developed original J2000g and helped to enhance the model. F.M. and M.F. participated in field work. M.F. carried out soil analysis. All authors continuously discussed the results and developed the analysis further. F.M., M.F. and P.K. commented on and/or edited the manuscript.

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Table 1. Basic information of selected basins in the study region. Data sources are described in Sect. 2.2.

Lake name	Elev. (m a.s.l.)	Lake center		Basin area (km^2)	Lake area (km^2)	Land cover (%)				
		Lat	Long			Lake	Glacier	Grassland	Wetland	Barren land
Nam Co	4725	30°42	90°33	10760	1950	18	2	39	8	33
Tangra Yumco	4540	31°00	86°34	9010	830	9	0.96	31	0.4	59
Paiku Co	4585	28°55	85°35	2380	270	10	6.5	43	0.5	40
Mapam Yumco	4580	30°42	81°28	4440	420	10	1.5	64	2.5	22

Table 2. Lake-level and water-volume changes derived from LEGOS data for the four studied lakes.

Lake name	Start date	Start volume (km^3)	Start level (m)	End date	End volume (km^3)	End level (m)	Δ Lake volume ($km^3\ yr^{-1}$)	Δ Lake level ($m\ yr^{-1}$)
Nam Co	27/09/2001	1.3	4722.683	01/10/2010	5.3	4724.697	0.44	0.22
Tangra Yumco	07/10/2001	0	4533.997	25/10/2009	1.7	4535.987	0.21	0.25
Paiku Co	02/06/2004	0	4578.067	04/03/2008	-0.08	4577.768	-0.02	-0.07
Mapam Yumco	30/10/2003	0.02	4585.551	21/11/2009	-0.1	4585.231	-0.01	-0.05

Table 3. Soil parameters used as input for the hydrological modeling.

Combination land cover – slope	Soil depth [cm]	Field capacity							
		Total [mm]	0-1 dm [mm/dm]	1-2 dm [mm/dm]	2-3 dm [mm/dm]	3-4 dm [mm/dm]	4-5 dm [mm/dm]	5-6 dm [mm/dm]	6-7 dm [mm/dm]
wetland	70	236	60	60	60	14	14	14	14
grassland <15°	70	120	18	18	18	18	16	16	16
grassland >15°	40	68	18	18	16	16	-	-	-
barren land <5°	20	14	7	7	-	-	-	-	-
barren land >5°	10	7	7	-	-	-	-	-	-

Table 4. Mean annual ~~W~~water-balance components, water-budget and lake-level changes for the four studied lake basins for the study period 2001-2010~~.~~ derived from the reference run. The variation ranges of the mean annual water-balance components correspond to model runs with precipitation-scaling factors ±0.05.

	Western basin →			Eastern basin
	Mapam Yumco	**Paiku Co**	**Tangra Yumco**	**Nam Co**
Water-balance components [mm yr^{-1}]				
Land				
Precipitation	230 (±24)	250 (±15)	300 (±20)	420 (±27)
AET ~~(AET/precip.)~~	170 ~~(0.74)~~ (±9)	180 ~~(0.72)~~ (±5)	210 ~~(0.70)~~ (±7)	290 ~~(0.69)~~ (±8)
Land runoff	60 (±14)	70 (±8)	90 (±12)	130 (±18)
Glacier				
Precipitation	330 (±33)	480 (±28)	330 (±22)	560 (±35)
Glacier runoff	600 (±8)	320 (±4)	1320 (±12)	1320 (±4)
Lake				
On-lake precipitation	90 (±9)	140 (±8)	150 (±10)	290 (±18)
Lake evaporation	710 (-)	910 (-)	840 (-)	770 (-)
Net evaporation	620 (±9)	770 (±8)	690 (±10)	580 (±18)
Water-budget [km³ yr^{-1}]				
Water gain				
Land runoff (% of total basin runoff)	0.23 (85)	0.14 (70)	0.70 (86)	1.15 (81)
Glacier runoff (% of total basin runoff)	0.04 (15)	0.06 (30)	0.11 (14)	0.27 (19)
Water loss				
Net evaporation	-0.26	-0.22	-0.57	-0.95
Net water-budget				
Lake-volume change	0.01	-0.02	0.24	0.47
Lake-level [m yr^{-1}]				
Simulated	0.02	-0.07	0.29	0.24
Zhang et al. (2011) (GLAS/ICESat 2003-2009)	-0.02	-0.04	0.26	0.25
Phan et al. (2012) (GLAS/ICESat 2003-2009)	-0.043	-0.118	0.291	0.230
LEGOS*	-0.05	-0.07	0.25	0.22

*Mean annual lake-level rates for the studied basins correspond to following time periods: Nam Co – 2001-2010; Tangra Yumco – 2001-2009; Paiku Co – 2004-2008; Mapam Yumco – 2003-2009.

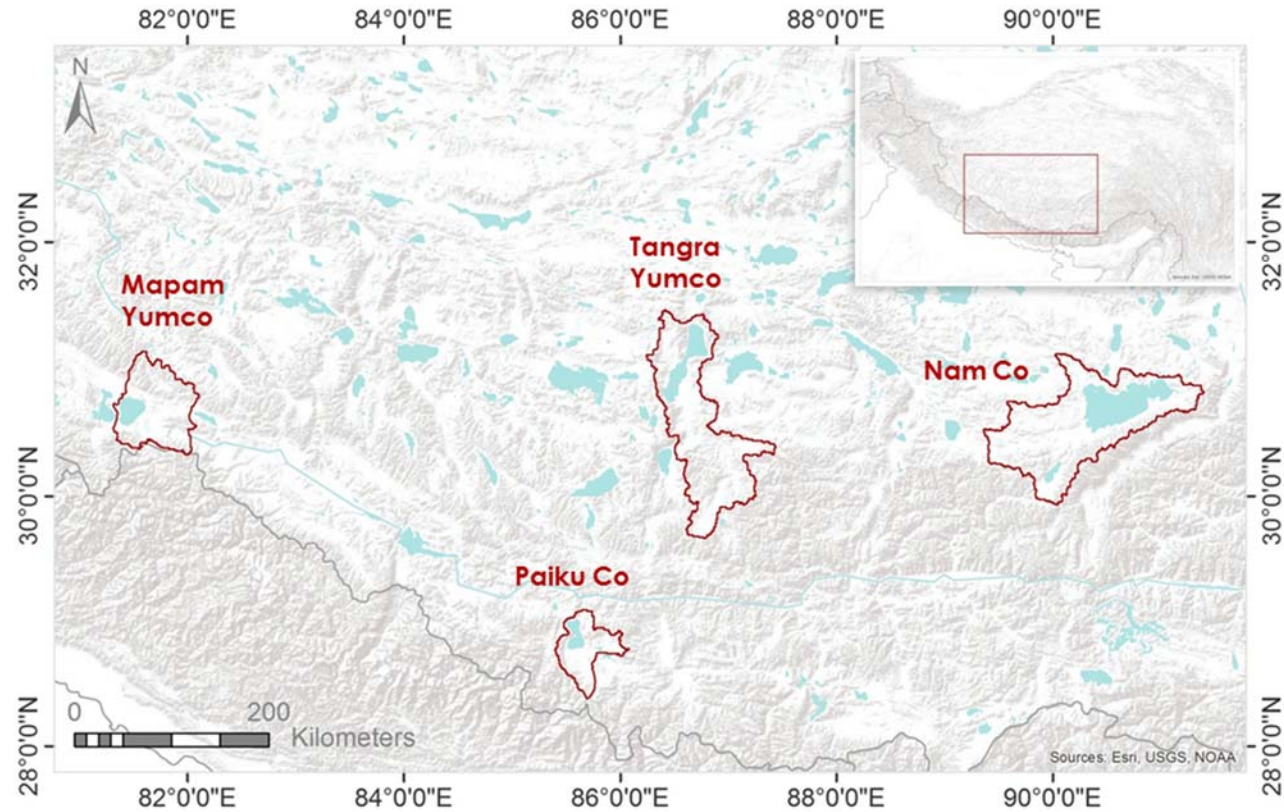


Figure 1. Location of the study region comprising four selected closed lake basins.

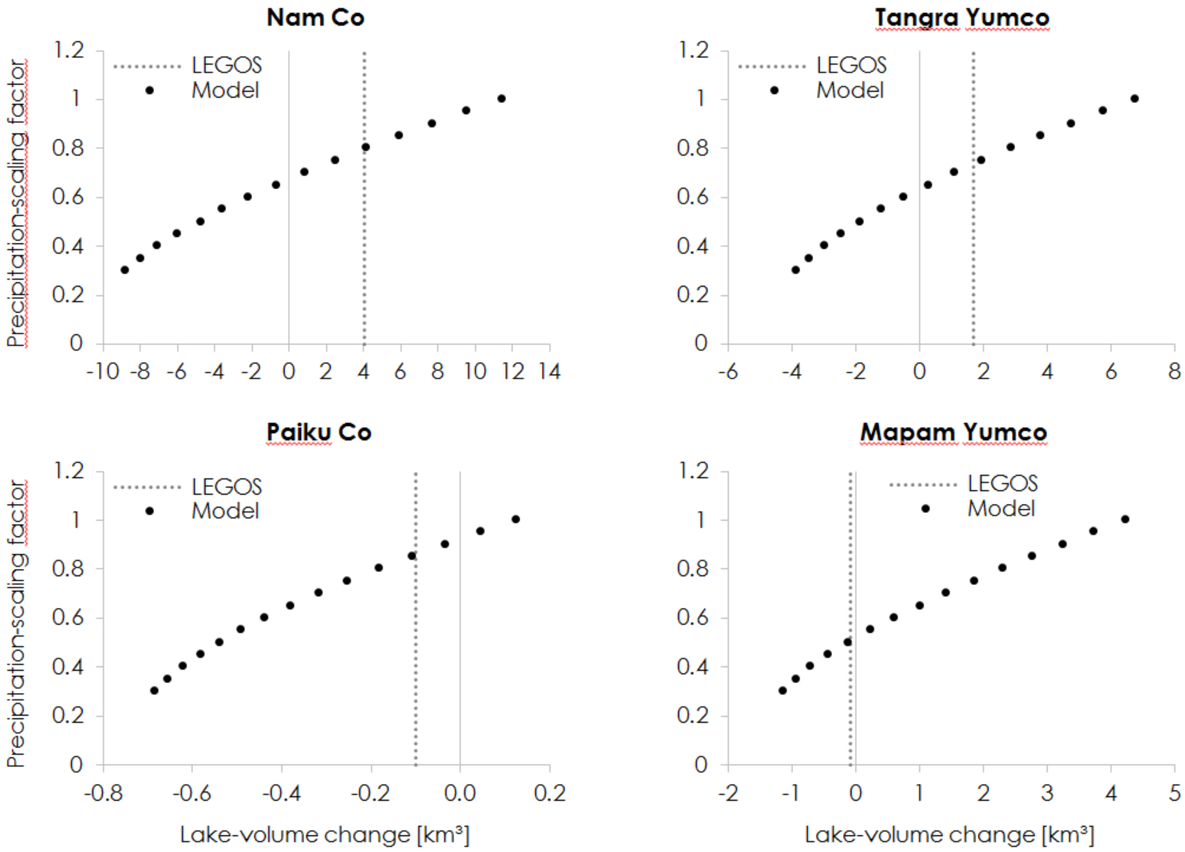
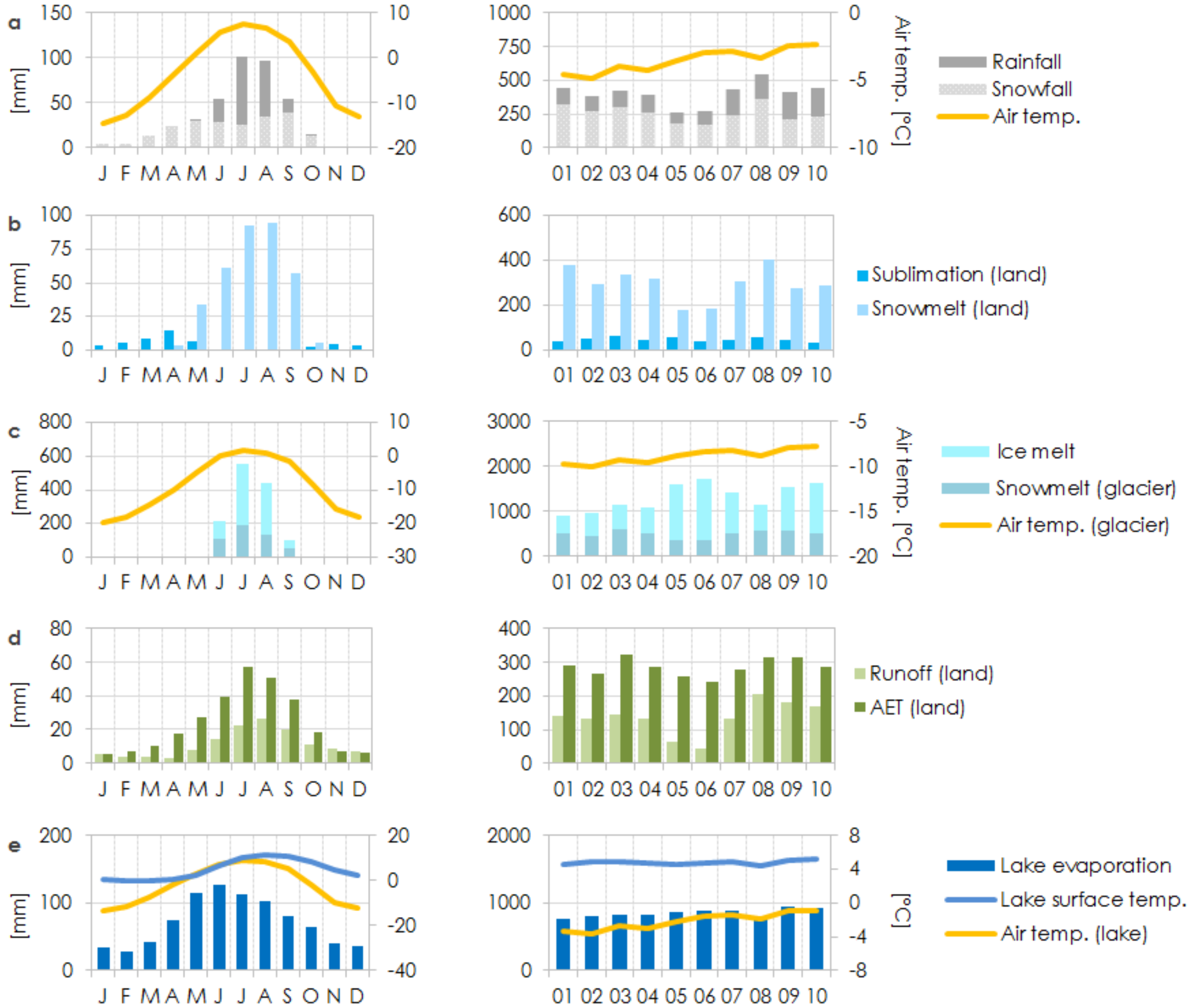


Figure 2. Model-simulated lake-volume changes for Nam Co, Tangra Yumo, Paiku Co and Mapam Yumco for the time periods given in Table 2 using precipitation-scaling factors varying between 0.3 and 1.0. Dotted line indicates lake-volume changes derived from remote sensing data provided by LEGOS. At the point where model dots are closest to the dotted line ~~is how~~ was taken as the precipitation-scaling factor ~~was set~~ for each basin.



~~Figure 3. Mean monthly and inter-annual variations (2001-2010) of modeled hydro-climatological components in the Nam Co basin. a) Basin-wide air temperature, rainfall, snowfall. b) Snow sublimation and snowmelt for the non-glacierized land surface. c) Glacier-wide air temperature and glacier melt (snow and ice melt). d) Evapotranspiration and runoff from the non-glacierized land surface. e) Air temperature over the lake, water surface temperature and evaporation from the lake.~~

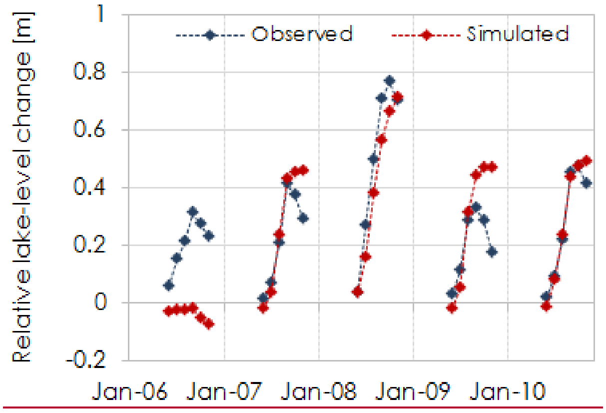
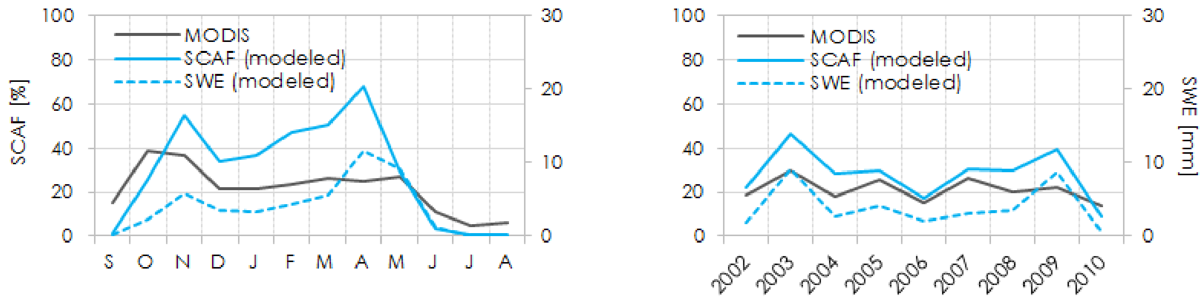


Figure 3. Monthly-averaged lake-level observations from the Nam Co (blue) versus simulated lake levels (red) for the June-November period of the years 2006 through 2010.



~~Figure 4. Mean monthly and inter-annual variations of modeled snow water equivalent (SWE) and snow-covered area fraction (SCAF) versus SCAF derived from MODIS for the Nam Co basin.~~

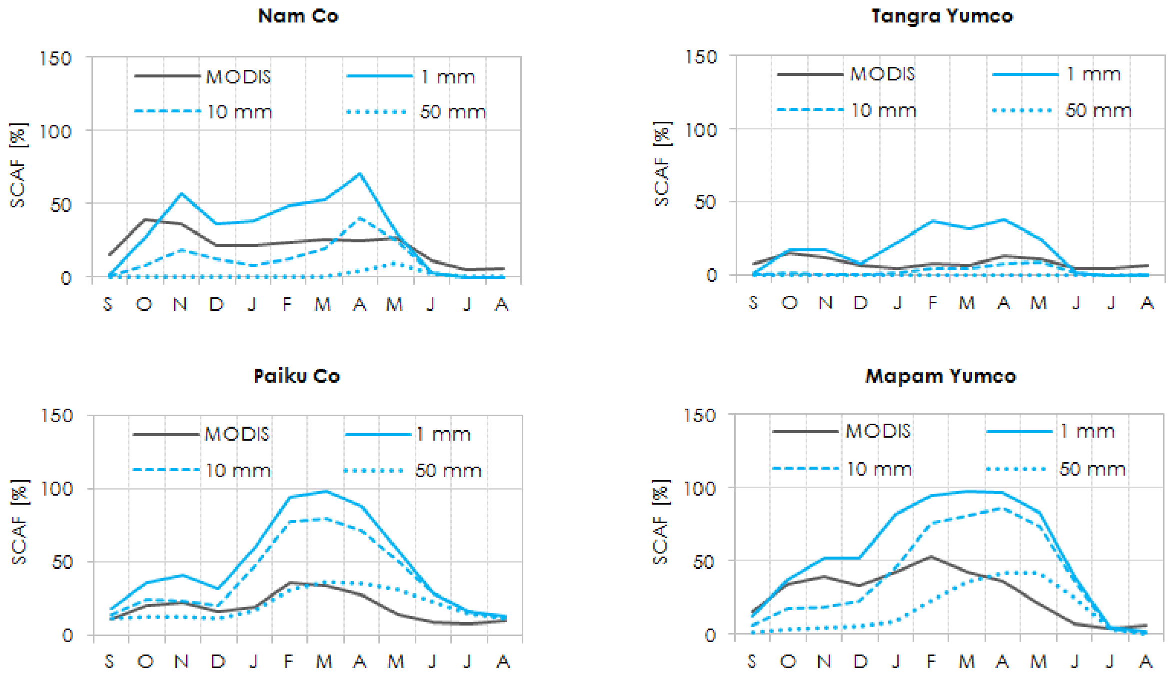


Figure 4. Mean monthly modeled-derived SCAF (blue) using SWE > 1 mm (solid line), > 10 mm (dashed line), and > 50 mm (dotted line) versus SCAF derived from MODIS (black) for the four study basins.

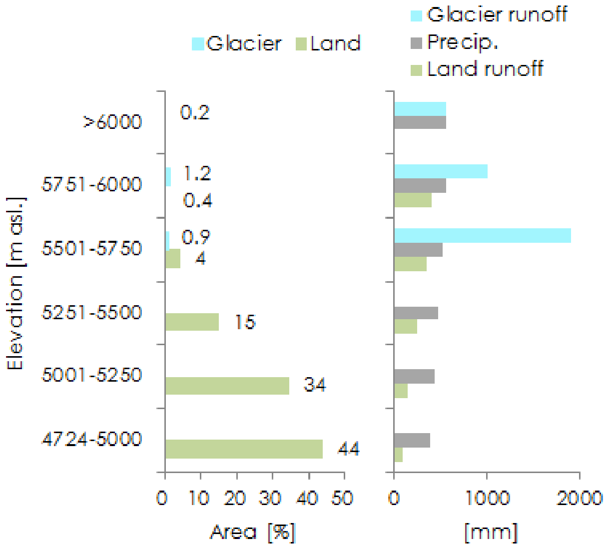


Figure 5. Hypsometry of non-glacierized land areas and glacier areas based on mean elevations of single model entities for the Nam Co basin (left panel). Variability of precipitation and runoff from non-glacierized land areas and glacier areas related to altitude (right panel).

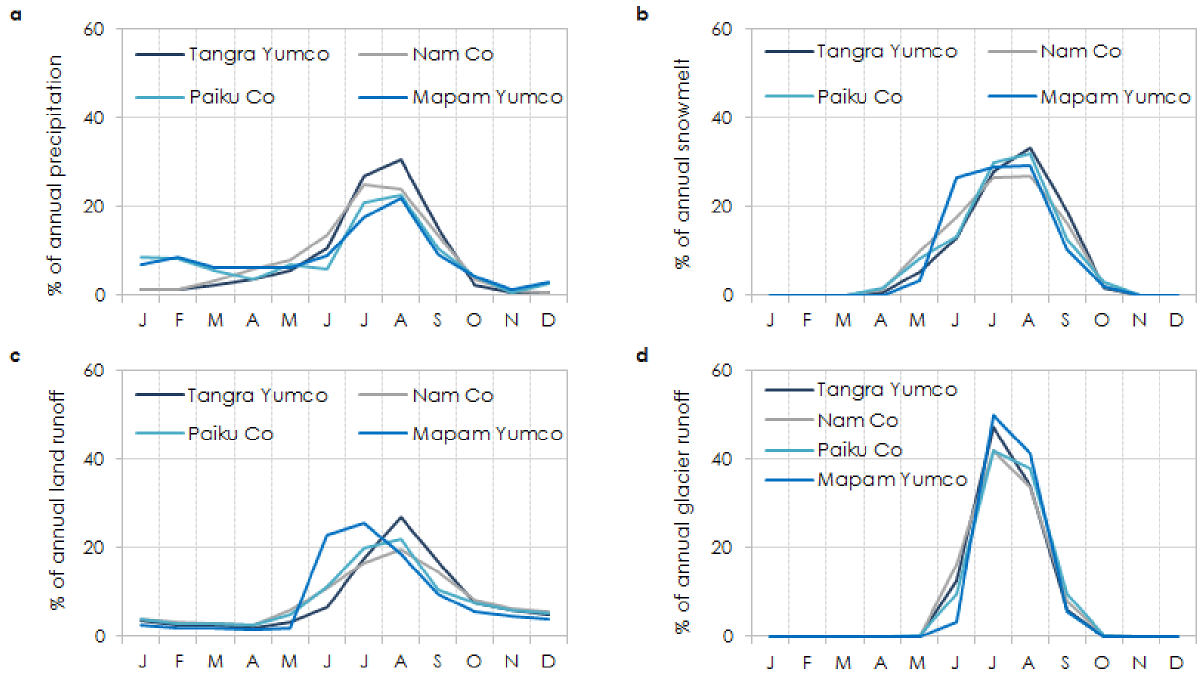
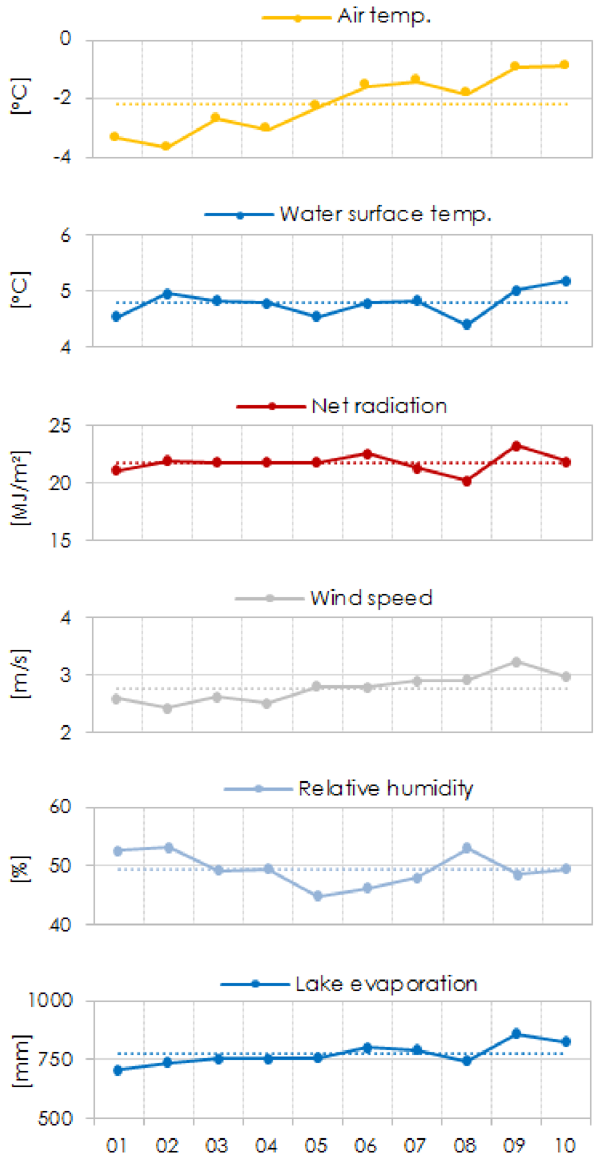


Figure 5. (a) Monthly percentage of annual precipitation, (b) snowmelt from non-glacierized land areas, (c) runoff from non-glacierized land areas, and (d) glacier runoff for the four studied basins.



~~Figure 6. Inter-annual variations of modeled lake-surface water temperature, lake evaporation, and various climate factors (air temperature, net radiation, wind speed, relative humidity) over the lake Nam Co. Dotted lines represent the corresponding 10-year annual means.~~

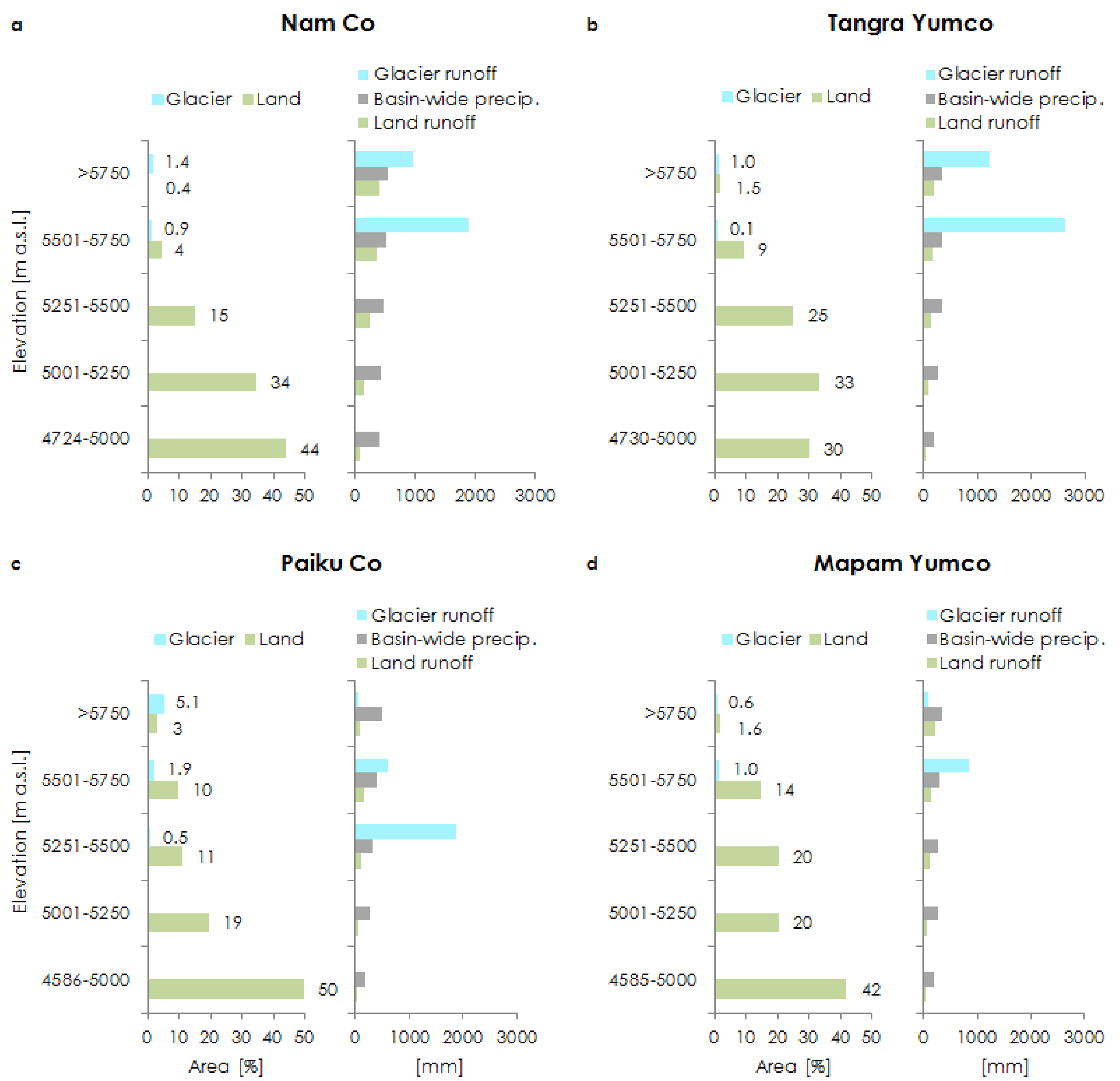


Figure 6. (a-d, left panels) Hypsometry of glacier and non-glacierized areas based on mean elevations of respective model entities for the four studied basin. (a-d, right panels) Variability of precipitation and runoff from glacier and non-glacierized areas related to altitude for the four studied basins.

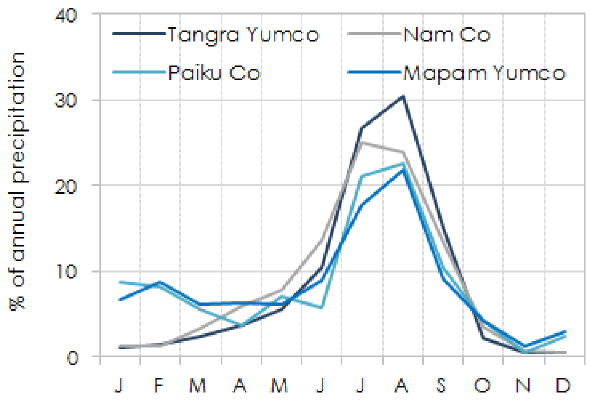


Figure 7. Monthly percentage of annual precipitation for the four studied basins.

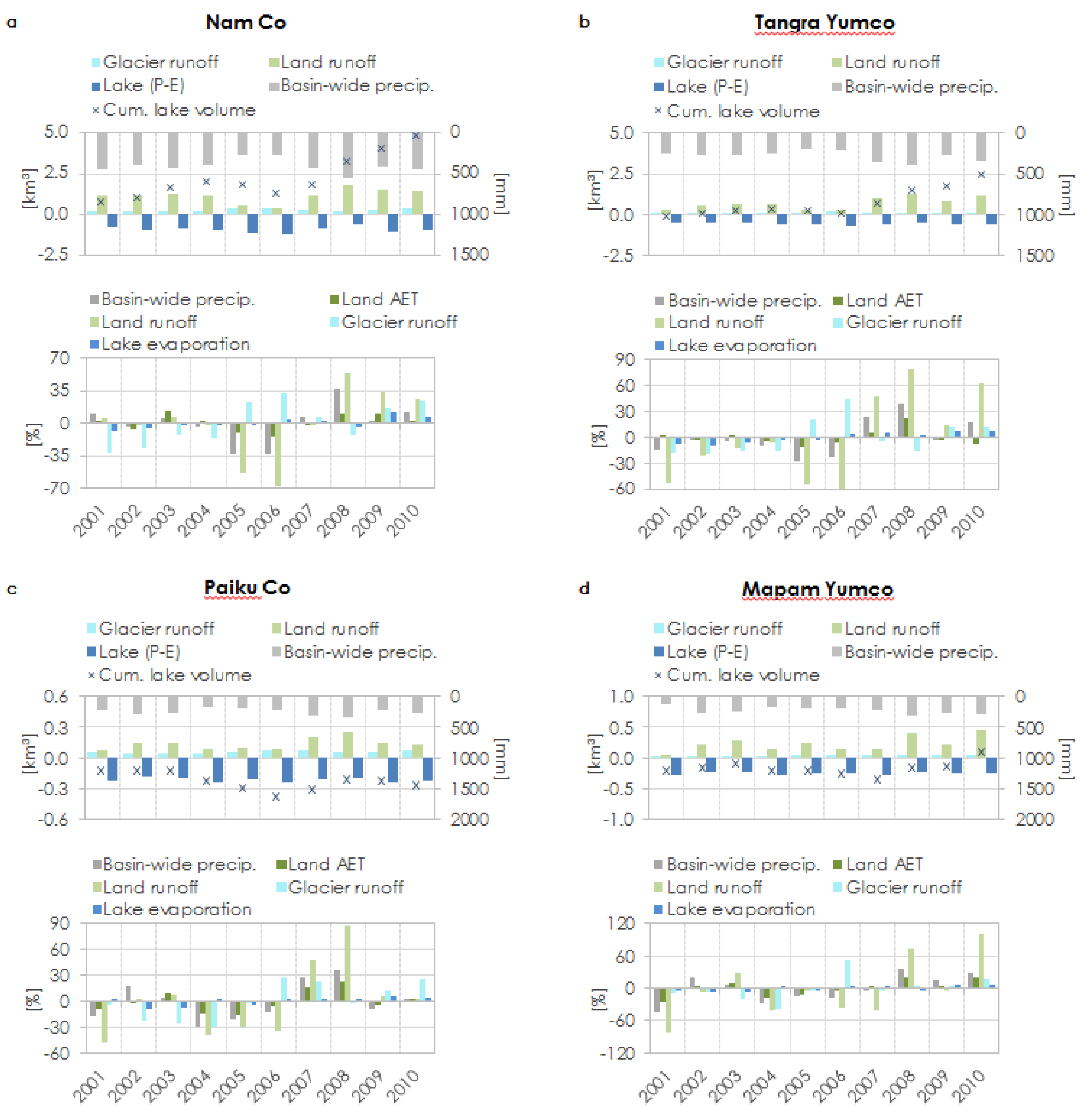


Figure ~~8~~7. (a-d, upper panels) Cumulative lake-volume change (km³), contribution of several water-balance components (km³) to lake-volume change and annual basin-wide precipitation amounts (mm yr^{-1}) for the four studied basins. (a-d, lower panels) Annual percentage deviations from the 10-year average of several water-balance components for the four studied basins.